THE UNIVERSITY OF ALBERTA

A SYSTEM OF STANDARDIZED BIOMECHANICAL FORCE MEASURES

by

ROBERT KENNETH JENSEN

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies for acceptance, a thesis entitled "A System of Standardized Biomechanical Force Measures" in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

The purpose of the study was to present and evaluate a system of biomechanical force measures which relate to physical education skills. The system was based on single segment rotation. Constrained, non-centroidal, plane rotation of a rigid body was used as the basic model. A skill was selected and analyzed into the component body segment rotations judged to be of importance to it. Those movements were then evaluated under rotational load conditions appropriate for the skill. A training program was administered and the effects of the program judged in terms of the changes in the single segment responses and the performance of the skill.

The system was applied to the skill of front crawl swimming speed. Shoulder extension and elbow extension were selected as the single segment responses to be tested. A resistance moment proportional to the square of the velocity was produced by means of a rotary torque actuator and a system of control valves. The moment applied to a lever arm was analyzed as the peak force at the starting angle for the static efforts and impulse and work output for the dynamic efforts. Eight criterion measures were used in the study. A six week swimming

training program was the independent variable in an experiment to see if the criterion measures changed as a result of training. Four factors were used in the study. The Groups factor consisted of an experimental and a control level with each group composed of twenty-one boys eight to eleven years old. The two groups were divided into three subgroups on the basis of initial swimming ability (Ability factor). Testing took place prior to and after three weeks and six weeks of the training program (Days factor). The four trials for each test were used as the levels of the Trials factor. The relationship between the Ability levels and the criterion measures was also investigated.

Swimming training produced significant changes in swim performance over the training period but the stimulus was found to be insufficient for the criterion variables. None of the interactions between Groups and testing Days was significant. Three of the criterion variables, shoulder extension impulse for the initial segment of the force curve, shoulder extension work output and elbow extension work output, were significantly different for the three levels of initial swimming Ability. Suggestions are made for improving the testing technique and for further applications of the system.

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NOMENCLATURE

F	Force.
F_C	Tangental component of the muscle contraction forces.
F_E	Tangental component of the external resistance forces.
F_G	Force due to gravity.
F_p	Horizontal swim propulsion force.
G	Centre of gravity.
I_e	Moment of inertia of the apparatus.
I_O	Moment of inertia about the axis of rotation.
M_A	Moment of force in the direction of muscle contraction.
M_O	Moment of force about the axis of rotation.
M_R	Moment of force in the direction of the external resistance.
m	Mass.
P	Power.
p	Pressure.
Q	Flow rate.
R	Horizontal resistance during swimming.
r_C	Radius from the axis of rotation to F_C.
r_E	Radius from the axis of rotation to F_E.
r_G	Radius from the axis of rotation to G.
V_{ARB}	An arbitrary voltage scale with zero as null and ± 3000 as full scale.
v	Horizontal velocity during swimming.
W	Work output.

α Angular acceleration.

η Sensitivity.

θ Angular displacement.

ν Kinematic viscosity.

ω Angular velocity.

CHAPTER I

THE PROBLEM

Evaluation of the biomechanical forces which man can use in his environment has been a recurring problem in physical education research. Traditionally, such measures have been taken without adequate regard for their theoretical basis, a trend criticized by Kroemer (1970):

1. Terminology is often inadequately defined, inappropriate or imprecise.

2. Biomechanical principles are given insufficient consideration.

3. Instrumentation is inadequate.

4. Experimental procedures and analyses are not clearly reported.

5. There is a concentration on static efforts whereas most activities consist of dynamic efforts.

The end product of any motor response is the application of force to change man's environment or man in relation to his environment. Force patterns for the various responses need to be known so that changes can be produced to improve the responses. The measurement

and manipulation of force patterns under laboratory conditions has been a major avenue of biomechanical research since the work of Hill (1922). Unfortunately, very little of this knowledge has been applied to physical education skills. The main concern of physical educators has been with the development of practical measures modelled on specific skills, such as the jump tests of 'power' (McCloy and Young, 1954, Ch. 9).

The need exists for a system of biomechanical force measures which relate logically and empirically to physical education skills. The problem investigated in this dissertation was the presentation of the rationale for a system of biomechanical force measures. An evaluation of the system was made by selecting measures appropriate to the skill of front crawl swimming speed and seeing if the measures differentiated between levels of swimming ability, and changed as a result of swimming training.

Established physical education measures have been in general based on multisegment movements. Multisegment movements can be attributed to the plane motion of each segment about axes created by the joints (Plagenhoef, 1971, p. 1) with rotation explained in terms of the effective forces (Beer and Johnston, 1962, pp. 622-627, 641-644). Each rotating segment involves a number of

forces, so that as the number of segments in a movement increases, the number of potential variables also increases. Rotation of a single segment about a joint axis can be considered to be mechanically the simplest unit of analysis (Figure 1). A multisegment test of the biomechanical forces involved in a skill such as front crawl swimming would require the simultaneous measurement of several parameters and effective control of the remaining variables would be necessary. Tests based on a single segment reduce the complexity of analysis to the variables illustrated in Figure 1. A further reduction of the analysis would involve individual muscle forces and segment weight, accurate measurement of which is considered exceptionally difficult if not impossible. The approach advocated in this study is stabilization of the body segments not being tested with the joint axis deemed fixed and analysis of the response in terms of constrained, noncentroidal, plane rotation of a body segment considered as a rigid body.

Static or dynamic analysis can be applied to the rotational response. If the resistance moment is opposite and equal to the applied moment of force and all other forces balance out the body is said to be in equilibrium:

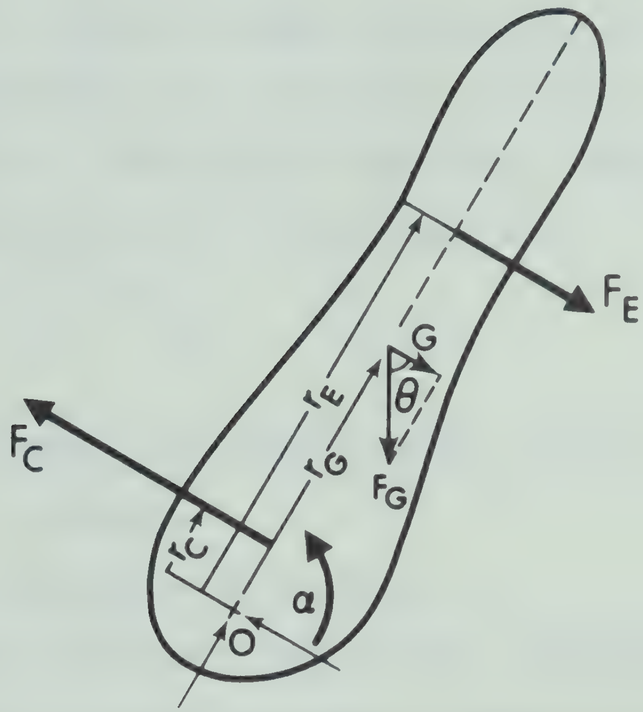


FIGURE 1

Forces Acting on a Body Segment

$$M_A = M_R \qquad (1)$$

where

M_A = applied moment

M_R = resistance moment.

In situations where the body is initially at rest, it will, in accordance with Newton's First Law of Motion, remain at rest. This is the case with static efforts. Dynamic efforts involve an inertial term:

$$M_A = I_o\alpha + M_R \qquad (2)$$

where

I_o = moment of inertia about the axis of rotation

α = angular acceleration.

This equation is derived from Newton's Second Law of Motion. Moment of inertia and the resistance moment constitute the load opposing movement and each can be varied experimentally.

The limits placed on each effort can be varied. In this context, effort is defined as the period over which there is an applied moment. Limits for the effort can be time or displacement based. An effort is either transient or part of a cycle of a periodic system. In the latter case, frequency and the overall limits for the system can be varied. Thus a static effort could be

measured over a set time interval, a dynamic effort over a particular displacement range and a repeated dynamic effort at a set cadence could be monitored over a given time period. These arguments are applicable to all combinations of load conditions. The experimental situation consists then, of selecting a load, setting displacement or time limits for the particular planar movement, and measuring the applied moment. A further variable, which cannot be so readily controlled, is the willingness of the subject (S) to give a maximum effort. This facet the experimenter (E) tries to maintain through explicit instructions and continual encouragement, and evaluates as reliability.

Research based on constrained, noncentroidal, plane rotation models has been mainly concerned with the effect of load on force and velocity (Chapter II). Most of this research would be classified as general biomechanics (Contini, 1963). The present work is concerned with applied biomechanics; the application of mechanical principles and general research findings to the skills of physical education. It is theoretically possible to describe these skills in terms of the rotational component forces creating them. The approach advocated in this work is to select the skill to be analyzed, examine it to determine the principal rotary movements and test the

movements under load, displacement and/or time conditions which are appropriate for the skill.

PROBLEMS

1. To develop the rationale for a system of biomechanical force measures based on plane rotation of body segments.

2. To illustrate the application of this system by selecting measures thought to be appropriate to the skill of front crawl swimming speed and seeing if those measures:

   a. differentiate between levels of swimming ability.

   b. change as a result of a training program for the skill.

SUB-PROBLEMS

1. To devise apparatus to measure the applied moment, angular displacement and time parameters for dynamic efforts against loads appropriate for the selected skill, and applied moment and time for static efforts.

2. To examine the measurement characteristics of the apparatus.

3. To formulate a set of conditions for the measurement of segmental rotation.

4. To design and implement an experiment to

determine:

a. the effect of a six week training program for beginning competitive swimmers on appropriate derived measures for the rotational movements thought to be of importance to the skill.

b. differences between the measures for initial skill levels.

DELIMITATIONS

1. Evaluation of the system was restricted to one experiment on a single skill.

2. Subjective judgements were involved in the selection of the movements, loads and derived measures. These judgements were supported by rational and empirical evidence.

3. The analysis was based on the applied moment and no attempt was made to evaluate the relative contribution of the inertial and resistance moment terms (Equation 2).

4. The age, ability level and number of <u>Ss</u> delimited the generalization of results.

CHAPTER II

RELATED LITERATURE

The literature relevant to the study is concerned with:

1. Rotational forces which develop about joint axes.

2. The application of estimates and measures of these forces to the skills of physical education, and in particular front crawl swimming speed.

STATIC ROTATIONAL FORCE

A considerable amount of physical education research has been devoted to finding the maximum force available within the range of the various multisegment and single segment movements of man. Justification of such investigations has usually been in terms of the need to know the maximum force for a particular muscle or group of muscles. The most comprehensive system based on this approach has been the cable-tension method developed by Clarke (1953). A more enlightened approach was used by Singh and Karpovich (1966). They were concerned with variations in the static moment of force throughout a range

[illegible]

of movement and compared the static moments for the condition of rest and for uniform concentric and eccentric velocity. Studies of this nature have direct application to skills such as raising and lowering weights. The dynamometer designed by Singh and Karpovich measured elbow flexion and extension and consisted of a lever arm which paralleled the action of the forearm, a handle, an electric motor and strain gauges to measure the applied moment. The model used was constrained, noncentroidal, plane rotation of a body segment in equilibrium.

DYNAMIC ROTATIONAL FORCES

Two approaches have been used in the study of dynamic rotational forces:

1. Estimates of the moments of force, resultant forces and component forces have been made through data from kinematic analyses of segment rotation, and body segment parameters. This approach is referred to as segmental analysis.

2. Direct analysis involves physical measurement of the force, mass, displacement and time variables, as required.

Segmental Analysis

The most common method for collecting kinematic data for segmental analyses is cinematography.

Plagenhoef (1966, 1968, 1971) has been a principal advocate of this approach. The body is treated as a system of links with segment rotation referenced to a fixed point such as a foot on the floor. Input data include body weight, and angular position, length, centre of gravity radius and radius of gyration for each of the segments being analyzed. From these data, angular velocity and acceleration, horizontal, vertical, resultant and moment of force for the segments, and total body centre of gravity are calculated. Adaptions of the method include the use of a relatively stable point such as the hip in swimming or the total body centre of gravity as the reference point.

Segmental analysis has the advantage of permitting a complete, three dimensional reduction of a skill into its component forces. Its limitations are based on questions of accuracy and precision.

1. Most body segment parameters cannot be measured directly. Estimates based on studies of cadavers and supplemented by girth and volume measures of the athlete (Plagenhoef, 1971, Chapter 3; Dempster, 1955) are of questionable accuracy.

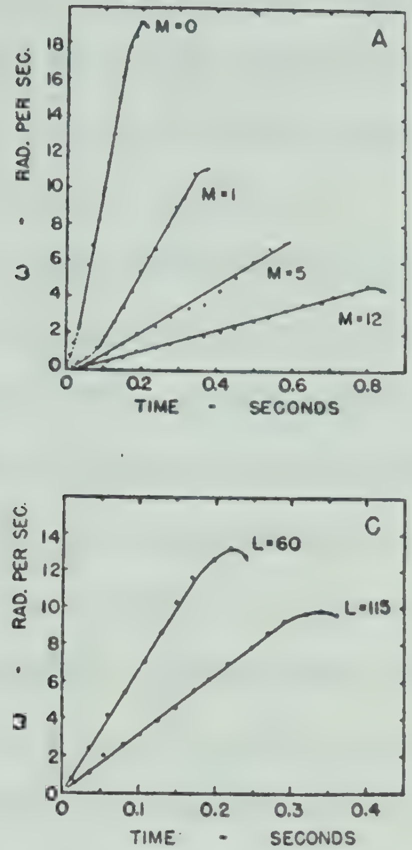
2. Experimental control of physical education skills is difficult. Between subjects and within subject variations are often due to uncontrolled sources of variance rather than to the variable being manipulated. Segmental

analysis has been used as a descriptive technique rather than as a method of experimentation.

Direct Analysis

Direct analysis has been mainly used to study the effect of load variation on the response of the rotating segment. The load can be varied by manipulating the resistance moment and/or inertial components. The complexity of measuring each of the segments in a multi-segment movement has restricted application to single segment movements.

A study of the effect of varying the inertial load and the resistance moment load was carried out by Dern, Levene and Blair (1947). Angular velocity versus time relationships for elbow flexion (Figure 2) showed that for most of the contraction period the angular acceleration was constant. Thus, as the moment of inertia for any one contraction was constant, the moment of force was also constant. The curves for inertial loads indicated an initial period of increasing acceleration, and thus force, an extended period of constant force and a final period of decreasing force. Curves for resistance moment loads showed the phase of constant force and a short duration phase of decreasing force. In these cases the force was the sum of the applied and resistance moments and remained at zero until the former exceeded the latter and displacement occurred. The



M = Inertial load mass (kg)

L = Resistance moment load (kg-cm)

FIGURE 2

Angular Velocity for Inertial and Resistance Moment Loads (Dern, Levene and Blair, 1947)

experiments of Dern, Levene and Blair involved a small number of subjects with few contractions per subject, however, and the interpretations were mainly based on the results of a single subject.

A further experiment involving a resistance moment load was conducted by Seireg, Baz and Patel (1971). Shoulder rotation in the saggital plane was paralleled by the action of two cylinders with dimensions similar to the arm. One cylinder was immersed in water. The strain produced by inertia, gravity, bouyancy and drag on the cylinders, and angular displacement were measured. The strain gauge circuits used cancelled the effects of inertia and gravity. Graphs of the square of angular velocity, and the drag moment, with respect to time, showed a constant proportionality. The relationships between normalized angular displacement and normalized time were similar to the curves of Dempster (1961) and the equations of Slote and Stone (1963) for unloaded segment rotation. Results for the velocity sensitive drag load used by Seireg, Baz and Patel (1971) showed a period of constant velocity (Figure 3) whereas curves for a constant resistance moment (Dern, Levene and Blair, 1947) showed constant acceleration through the middle range. Changing angular velocity under the first system increased the resistance moment, which had the overall effect of matching the resistance moment to the applied

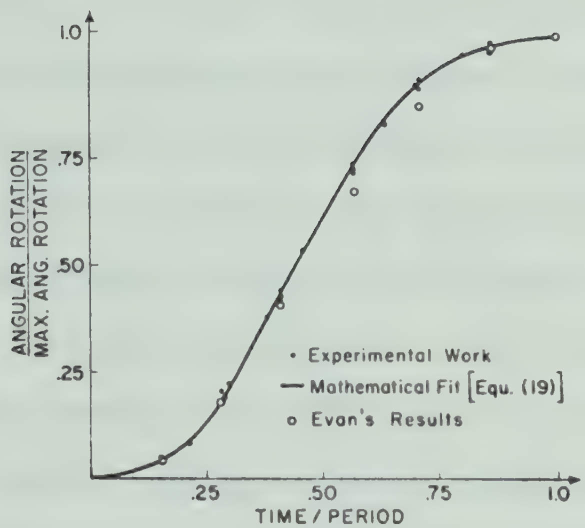


FIGURE 3

Normalized Displacement-Time Graph for Shoulder Rotation (Seireg, Baz and Patel, 1971)

moment. Availability of applied force greater than the resistance moment, under the second system produced angular acceleration. These studies then, demonstrated two distinct resistance moment load states.

Other devices based on resistance moments have been constructed. Constant velocity dynamometers have been developed for elbow (Singh and Karpovich, 1966) and ankle (Herman, Schaumburg and Reiner, 1967) movements. A more comprehensive device studied by Thistle, Hislop, Moffroid and Lowman (1966), was adaptable to a large number of rotational movements and showed promise as a testing and training instrument. The dynamometer's loading system was motor driven and at a constant angular velocity. A pilot study compared isokinetic training, progressive resistance exercise and isometric training with the results of a control group. Total work and peak moment were calculated. Over an eight week training period with four sessions per week, all training groups improved, with the isokinetic group showing the greatest improvement, whilst the control group showed a decreased performance. The above dynamometers maintained a constant velocity throughout the movement, a condition rarely encountered in non-standardized motor responses.

A fly-wheel has been used by Hill (1922) and Lupton (1922) to study the effect of inertia loads on

forearm flexion. Hill postulated that for work output to be maximum, the load would have to be barely moveable. The fly-wheel consisted of a series of different diameter pulleys and the load opposing muscle force was varied by using different pulleys. Work was calculated from the angular velocity, measured by a tachometer, and the moment of inertia for the fly-wheel. There was close agreement between theoretical and observed curves for work versus load and work versus contraction period.

The relationship between force and velocity was extensively investigated by Wilkie (1949). Static tension against a spring balance was measured at an angle of 100 degrees from the fully extended position for the elbow. A lever was constructed which was connected to the hand by a length of cable and paralleled the action of the forearm. Tension in the cable was varied by suspending weights on the lever. Velocity was recorded at the 100 degree angle. It has been shown by Hill (1938) that the shape of the force-velocity curve is represented by:

$$(F + a)\ (V + b) = (F_s + a)b \qquad (3)$$

where

F = force of contraction

V = velocity of shortening

F_s = force at zero speed

a, b = constants to align the observed points with the theoretical curve.

Wilkie found that with tensions less than 30 percent of static tension the experimental results did not fit the theoretical curve. In accordance with Newton's Second Law, the characteristic equation was modified to allow for the inertia of the forearm and apparatus. The modified equation adequately described the force-velocity data but was deficient for velocity-time data (Figure 4) collected over the movement range. The model was revised and allowance made for an elastic element in series with the contractile element of muscle (Hill, 1949). Energy was stored in the elastic element during initial acceleration and released as the velocity approached a steady value. The mode of rise for velocity with the series elastic/contractile model adequately explained the experimental data (Figure 4). The curves showed an initial period of increasing acceleration, a period of constant acceleration and a period of zero acceleration. The values used for these curves were transposed to angular measures and found to agree with the results for the inertia experiments of Dern, Levene and Blair (1947).

Further applications of the series elastic/contractile model to the in situ muscle have been made. Bouisset, Goubel and Lestienne (1968) studied submaximal contractions for horizontal elbow flexion against light inertias. Initial tension without displacement was

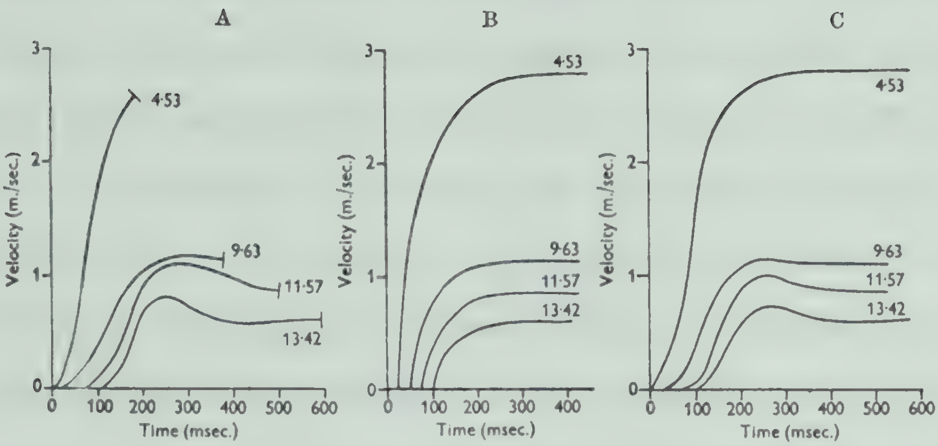


Fig. 5. Velocity-time curves. Subject D.W. A, Experimental curves. The bar at end of each curve marks the point at which lever hits catch, just after its velocity has been measured for calibration. Subsequent rapid and irregular fall in velocity not shown. B, Theoretical curves. Calculated from $(P_0+a)b/(V+b)-a=F+MdV/dt$ (see Appendix A). C, Theoretical curves. Calculated electrically from equation 2, p. 261. Figures on graphs indicate tension (megadynes) against which pull was made.

FIGURE 4

Observed and Theoretical Velocity-Time

Curves (Wilkie, 1949)

demonstrated and related to electromyographic traces of m. biceps brachii. Cavanagh and Grieve (1970) used a force transducer to record the tension at the hand for the Wilkie lever. After correction for inertial and gravitational effects, force and velocity were related to time and shown to follow the anticipated pattern. The rate of stretch for the elastic element was calculated from the difference between the measured velocity and velocity of muscle contraction as indicated by measures of velocity over periods of maximum or minimum force. Elastic potential energy stored was compared with external energy released.

Power has been commonly used as a measure of forceful movements. Koepke and Whitson (1940) derived acceleration and velocity from displacement/time data for a series of hand weights and calculated maximum instantaneous power for sweeping motions of the hand. They concluded that varying the weight did not appreciably affect the power output. Glencross (1963) used a lever/pulley system mounted on an axle, estimated the kinetic energy for a rotational movement from the velocity attained and calculated average power by dividing total work by the time for the movement. This device was further investigated by Jensen (1963) who varied the weight on the pulley and demonstrated that the effect on power output was non-significant. A second study (Jensen, 1969) related power

to static force and unloaded velocity measures. It was found that static force at the starting point for the dynamic response was the best of the predictor variables.

Power output for an unloaded limb was studied by Slote and Stone (1963). Moment of force was calculated from the moment produced by the weight of the arm and the inertial term (Figure 1) for forearm flexion:

$$M_o = F_G(\cos\theta)r + I_o\alpha$$

where

F_G = weight of segment

r = radius to the c.g.

θ = angular displacement.

Curves for the three terms of the equation were graphed as a function of angular displacement. Work output was calculated as the area under the force/displacement curve.

$$W_{0\to\theta_o} = \int_0^{\theta_o} M_o \, d\theta$$

$$= F_G\, r \int_0^{\theta_o} \cos\theta \, d\theta + I_o \int_0^{\theta_o} \alpha \, d\theta$$

where

W = work.

Power, the time-rate of doing work, was given by:

$$P = \frac{dW}{dt}$$

$$= \frac{dW}{d\theta} \cdot \frac{d\theta}{dt}$$

$$= M_o\omega$$

where

P = power

ω = angular velocity.

The effect of inertial load on power output was investigated by Suggs (1969) using a single stroke lever system. The moment was measured by strain gauges on the lever arm and the angular velocity by a transducer mounted on the shaft. Kinetic energy at the end of the stroke was used as the measure of work output, and divided by time to give average power transmitted to the load:

$$P_e = \frac{I_e \omega^2}{2t}$$

where

I_e = moment of inertia of the apparatus.

As force is dependent upon velocity (Equation 3), it was hypothesized that maximum power output would occur when the external inertia was greater than the internal inertia and the resulting load produced a lower velocity. Curves of moment of force, angular velocity and normalized displacement, in terms of normalized time, were derived graphically from a force-velocity curve, and power output calculated as a function of inertial load. Close agreement was found between the theoretical and observed curves of power and maximum power output occurred with an external inertia six to ten times the mean value of the internal inertia.

The use of power as a parameter for measuring jumping performance has been queried by Adamson and Whitney (1969) and their discussion has ramifications for all transient, dynamic efforts. Power output for a vertical jump has been calculated from force platform traces as the product of force and the velocity derived from the force curve (Davies and Rennie, 1968). Other less sophisticated techniques have been used (Gray, Start and Glencross, 1962). Adamson and Whitney acknowledge that power production during force application can be measured from the kinetic energy developed, but see this as being of use in understanding power dissipation after completion of the effort rather than in assessing the height a person would jump. It is of greater use to know the momentum developed by the effort (impulse) for the jump (Ramey, 1970). Parameters which are appropriate for the skill being analyzed, have to be selected.

<u>Summary</u>

1. Segmental analysis has been mainly used as a descriptive technique.

2. Experiments with rotational movements under constant inertial or resistance moment loads have shown an extended period of constant acceleration.

3. It has been shown experimentally that when the resistance moment is velocity sensitive, the angular velocity tends to be constant.

Changes in the applied moment produce corresponding changes in the resistance moment.

4. Initial tension without displacement has been demonstrated, and explained in terms of the series elastic/contractile model of muscle. Under resistance moment loads, the tension has to be at least equal to the resistance.

5. Increases in total work output and peak moment of force, as a result of resistance training, have been demonstrated.

6. Studies of power output for rotational movements have shown:

a. Static force at the starting point could predict average power.

b. Variation of load probably affects power. Conflicting results have been reported.

7. The usefulness of power as a measure of jumping performance has been queried. A derived force measure which is appropriate for the particular skill should be used.

PROPULSIVE FORCES IN SWIMMING

The horizontal and vertical forces of swimming have been summarized by Faulkner (1967). In a vertical direction, buoyancy, body weight and lift determine the position of the swimmer in the water. Horizontally, the propulsive force depends upon muscle force, segment positioning and fluid forces about the segments. The resistance is the drag

created by boundary layer shear stress, pressure due to turbulence and wave resistance.

The actions of the arm in front crawl swimming involve motion in three planes (Plagenhoef, 1971, pp. 121-124). It is evident that lateral movements of the hand are used to produce a lift force (Brown and Councilman, 1971) which is combined with the drag force created by the longitudinal motion of the hand and arm. The resultant is the external force against which the muscular forces are applied.

Attempts have been made to measure the horizontal forces of swimming. Alley (1949) attached a line to the swimmer, released the line at controlled rates and measured the horizontal force exerted through the line. Drag was measured by towing the swimmer toward the dynamometer at the same speeds. Differences between the two measures at each speed were taken as the forces available for accelerating the swimmer. Councilman (1955) used a similar technique to study differences between different styles of front crawl. Magel (1970) found that with tethered swimming two force peaks were noticeable during each arm action.

Electrogoniometry has been used to measure angular displacement for the elbow and wrist during front crawl swimming (Ringer and Adrian, 1969). The elbow was shown to extend fully as the arm entered the water, flex and

then extend rapidly just prior to recovery. A period of forceful elbow extension was also evident in a segmental analysis by Plagenhoef (1971) and electromyographical traces of m. triceps brachii (Lewillie, 1971). These results suggest that the secondary force peak (Magel, 1970) could be largely due to the elbow action.

A simplified model of the arm has been used by Seireg, Baz and Patel (1971) to measure rotary drag forces. Their cylindrical model has limited application in explaining the forces resisting the arm action, however. The cylinder was made to move through the water whereas the arm segments during swimming are comparatively fixed in relation to the water, and the possibility of lift forces was not allowed for. The rowing action is mechanically analogous to the swimming stroke. Ishiko (1971) measured the bending strain of the oar and the acceleration of the boat during rowing and found the strain preceded the acceleration. He attributed the fact that the strain preceded the acceleration to the inertia of the oar as it was decelerated over the final phase of recovery, but the pattern is largely due to the force which has to be applied to bring the velocity of the oar in the water to a level where the propulsive force is equal to the drag of the boat. In accordance with Newton's Second Law of Motion, additional strain applied to the oar after this point will accelerate

the boat. The curves for strain showed a rapid rise to a peak and a gradual decline to the start of the recovery.

Similarities between rowing and swimming can be seen in the theoretical analysis of the dynamics of swimming presented by Kopsiva (1969). He recognized the

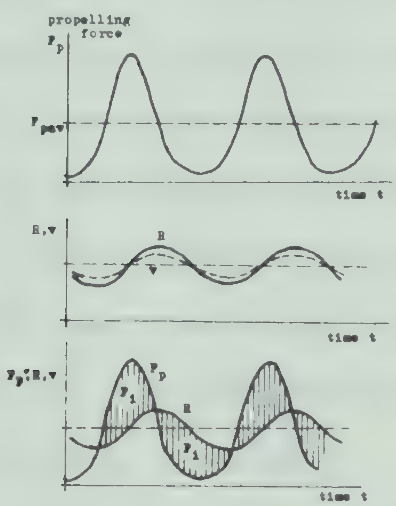


FIGURE 5

Horizontal Propulsive Force and Resistance Curves for Swimming (Kopsiva, 1969)

fluctuating nature of the propelling force and resistance. For simplicity, he plotted these fluctuations as sine waves (Figure 5). Resistance is the sum of resistance due to pressure, resistance due to friction and wave resistance and was calculated from swimming velocities and

estimates of body size. The propulsive force curve was represented as intersecting the resistance curve at its maxima and minima. At these points, resistance and thus velocity, are constant. As velocity is not changing, the propulsive force is equal to the resistance. At all other points, there is acceleration and the difference between the two curves is the inertial force. A method of calculating the propulsive force from the dimensions and velocity of the hand was given. The palm of the hand was regarded as a flat plate and dynamic pressure due to drag calculated. Direct measurement of propulsive force was in accordance with the method of Alley (1949). Plagenhoef (1971, pp. 152-158) has used Alley's results and segmental analysis to calculate the peak moments of force for the movements in front crawl swimming.

Summary

1. The motion of the arms during propulsion produces lift and drag forces against which muscle force is applied. The resistance produced is some function of velocity.

2. Two force peaks during each arm action have been measured. The second peak seems to relate to the elbow extension movement.

3. Muscle force is used initially to produce resistance forces about the arm which balance the

resistance of the body moving through the water. In accordance with Newton's Second Law of Motion, additional application of propulsive force accelerates the body.

CHAPTER III

PROCEDURES

General biomechanics is concerned with the basic principles of human motion and applied biomechanics deals with the application of the basic principles to the improvement of movement (Contini, 1963). The intent of this study was the systematic application of measures founded on general biomechanical principles to human movement skills. A system was developed which could be applied to most multisegment skills. The system was then used to evaluate the effect of a training program for front crawl swimming on the mechanical responses considered basic to the skill.

THE SYSTEM

The steps in the system are as follows:

1. Selection of a skill.

2. Analysis of the skill into the component single segment rotations judged to be of importance to it.

3. Selection of derived force measures appropriate for the skill being analyzed.

4. Evaluation of the skill.

5. Evaluation of the body segment responses

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against loads which are appropriate for the skill.

6. Manipulation of variables thought to affect the force patterns basic to the skill.

7. Re-evaluation of the skill and the body segment responses.

The body can be conceived as a chain of rigid, body segment links. Rotational force, due to muscle force and gravity, can produce rotational movement about the joints (Moffatt, Harris and Haslam, 1969). Human movement consists of relative movements between body segments, the force equations of which have been documented by Plagenhoef (1971, pp. 48-55). Segmental analysis provides the data necessary for this model but to date, no means of adequately measuring force directly, for multi-segment movements, has been developed. The greater flexibility of direct analysis makes this development highly desirable.

A simpler form of direct analysis is based on single segment rotation. If the joint is fixed anatomically, noncentroidal, plane rotation of a rigid body about a fixed axis can be used as a model (Beer and Johnston, 1962, pp. 643-644). Body segment displacements are large relative to tissue deformation for most segment movements and the assumption of a rigid body can be made (Moffatt, Harris and Haslam, 1969). Plane motion is

assumed, necessitating the restriction of the movement and forces to the one plane during experimentation. A further assumption is that of a fixed axis of rotation. Experimental apparatus can be constructed with a fixed axis but the human axis, the joint, is not as readily controlled. Anatomical stabilization is used to restrict the joint axis to a line approximating a fixed axis. The centroidal axis of the body segment and lever arm would be constant for each effort due to the mechanism used to attach the segment to the lever. Moment of inertia about the fixed axis of rotation could be obtained by means of the parallel axis theorem (Beer and Johnston, 1962, pp. 344-345). Intra-subject changes in the moment of inertia across trials and days would be expected to be small and apart from slight changes in the angle of attachment of muscles would not be expected to affect the applied moment. Free body diagrams for single segment rotation have been prepared by Plagenhoef (1971, pp. 28-46).

The selection of the single segment rotations considered important to the skill has to be justified rationally and empirically. Evidence is usually available from segmental and electromyographical analyses of the skill. Experimental evaluation of a selected rotational movement involves loading the segment with an

inertial and/or resistance moment load similar to the load on the segment during the performance of the skill. Variations of the load during the performance should be noted and if possible programmed into the experimental load. Limits over which the response is tested are set after examination of the skill. The load on the segment and the response limits are under the direct control of the experimenter and could be held constant for all <u>Ss</u> and tests or varied according to some criterion.

The effort is measured in terms of the applied moment (Equations 1 and 2). The inertial and resistance moment terms for dynamic responses could be evaluated but as the system is based on changes in the available muscle force, their relative contribution need not be known. Moment of inertia of the body segment being tested varies with the subject and thus is not under the control of the experimenter. However, the variable is also an integral part of the skill being analyzed, so the applied nature of the testing situation makes it appropriate.

Further analysis of the applied moment is based on an understanding of the role of the body segment in the skill being analyzed. Appropriate measures derived from the moment include:

1. Peak applied moment. Some skills require a

large force at a point to overcome a high resistance or to initiate high acceleration. Maximum force could be measured at an angle or for a specified movement range.

2. Work output. Some skills depend upon the amount of work which is applied. In terms of an applied moment acting through an angular displacement:

$$W_{1\to2} = \int_{\theta_1}^{\theta_2} M_A \, d\theta \qquad (4)$$

where

θ_1 θ_2 = angular limits.

3. Power. Skills such as bicycle racing depend not so much on the amount of work produced as on the rate at which work is produced. Average power can be calculated by dividing the work output by the time taken to produce the work. Power at any instant is given by:

$$P = M_A \, \omega \ .$$

Work and average power could be measured for a transient effort or for cyclic efforts.

4. Impulse and momentum. Skills which depend largely on changes in momentum, throwing and jumping being examples, should be analyzed in terms of impulse (Adamson and Whitney, 1969; Ramey, 1970). In the case of noncentroidal rotation of a rigid body in plane motion, the principle of impulse and momentum can be expressed

in terms of the applied moment:

$$\int_{t_1}^{t_2} M_A \, dt = I_o\omega_2 - I_o\omega_1 + \int_{t_1}^{t_2} M_R \, dt \qquad (5)$$

where

$t_1 \; t_2$ = time limits

ω_1 = initial angular velocity

ω_2 = final angular velocity.

In words, the impulse due to the applied moment is equal to the change in angular momentum plus the impulse due to the resistance moment.

As was indicated in the literature review, apparatus to measure the applied moment under static conditions has been developed and could probably be adapted to most rotational movements (Singh and Karpovich, 1966; Thistle, Hislop, Moffroid and Lowman, 1966). Apparatus for dynamic responses against inertial (Suggs, 1969) and resistance moment loads (Dern, Levene and Blair, 1949) could likewise be adapted for measuring the applied moment of the various movements. Further analysis of the applied moment could be handled at the graphical, analog or digital levels.

Manipulation of the applied moment variable involves a training program to develop the force due to muscle action by either subjecting the segment to direct

loads, such as in weight training, or by using the skill as a training stimulus. A judgement has to be made as to whether the skill will produce a sufficient stimulus to develop the applied moment. The training program is the independent variable and the derived force measures selected as appropriate to the skill are the criterion variables. All other relevant variables, such as load, displacement range, stabilization, environmental factors, test instructions and motivation, are held constant. Changes in the criterion variables are taken as indicating the effectiveness of the training program to develop the mechanical responses considered basic to the selected skill.

THE SKILL

Front crawl swimming speed was selected as the skill to be investigated. It was hypothesized that in an untrained group the load produced by the fluid forces during swimming would be a sufficient stimulus to develop the muscle forces used to propel the body.

The efficiency of the arm action in front crawl swimming has been shown to be far greater than the leg action (Adrian, Singh and Karpovich, 1966). As the analysis had to be restricted to the primary body segment rotations, leg actions were not tested. Wrist flexion and extension during propulsion is small and mainly

concerned with positioning (Ringer and Adrian, 1969). Shoulder extension and elbow extension would appear, from segmental analyses, to be the primary propulsive movements for front crawl swimming. Shoulder extension occurs throughout the underwater phase but appears most forceful from 150 degrees to 30 degrees* (Plagenhoef, 1971, pp. 121-127). The role of the elbow extension movement was considered in the literature review and found to be important for the swimming action. The range for trained swimmers was from approximately 70 degrees to the fully extended position.

A pilot segmental analysis was used to relate arm movements to horizontal swimming velocity (Appendix A). Shoulder extension was shown to be accompanied by a cyclic increase in forward velocity, with a further increase noticeable during the period of elbow extension. The force available from shoulder and elbow extension was greater than the resistance acting on the body and acceleration occurred.

THE EXPERIMENT

Independent Variable

Swimming training was used as the independent variable. A program modelled on the approach used for

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* All body position angles are taken from the anatomical position.

age-group swimmers was developed after consultation with a successful age-group coach. Improvement in swimming speed as a result of training is evident from documentation of race results. This study was concerned with the effect of swimming training on elbow and shoulder extension force.

Sample and Population

A sample of beginning competitive swimmers, eight to eleven years and interested in a six week swim training program, was recruited through the University of Alberta staff newspaper and from elementary schools in the vicinity of the University. A pre-pubescent age range was selected so as to avoid the problems of accelerated growth rates. Of the forty eight *Ss* selected from those who applied, one was unable to complete the program and a *S* had to be removed from each of the other five subgroups. Initial selection was on the basis of swimming ability and availability for testing and training.

Although the selection of the sample was incidental (Guilford, 1956, pp. 159-160) the method of recruiting swimmers could be taken as a standard method of starting a regional swim group. The hypothetical population corresponding to the sample was defined as boys between the ages of eight and eleven years, inclusive, who are beginning competitive swimming.

<u>Selection of the Criterion Variables</u>

The load against which the arm segments act during swim propulsion is primarily a velocity sensitive resistance moment (Kopsiva, 1969; Seireg, Baz and Patel, 1971). It was necessary to provide a load state for the dynamic tests of approximately the same type. The criterion variables used were based on the moment applied against the load.

Peak static applied moment at the starting angles for the two extension movements was measured for the following reasons. Firstly, initial force application occurs without displacement. The applied force must be greater than the shear forces and pressure forces created by changing the existing state (Shapiro, 1961, pp. 48-70) before motion can occur. Secondly, according to the series elastic/contractile model (Wilkie, 1949; Cavanagh and Grieve, 1970), part of the initial force application is stored as elastic energy which could be utilized during the response. Thirdly, immediately following the initial force application a period of high acceleration occurs to bring the segment to the velocity required for propulsion. The inertial component would be high during this period, necessitating a large applied moment which could approach the maximum moment available from muscle contraction. It was hypothesized that due to the size of the resistance

[illegible]

and inertial forces in the region of the starting angle, the applied moment would increase and this would be reflected as a change in the peak static moment.

Impulse for the applied moment was measured over an initial and an extended time period for both movements. As the resistance moment during swimming is velocity sensitive (Seireg, Baz and Patel, 1971) and the movement of the segment through water produces a period of constant velocity (Figure 3) two distinct stages were anticipated for the applied moment curve. The first stage, termed the leading edge, covered the rapid rise of the applied moment from the resting level to the second stage, that of near equilibrium. During the equilibrium stage changes in velocity would be minimal and the applied moment would approximate the resistance moment. The initial time period covered the leading edge of the signal and the extended time period, the leading edge and the equilibrium segment of the applied moment curve. The applied moment impulse during swimming produces a change in angular momentum which in turn affects the resistance moment impulse (Equation 5). The size of the resistance moment impulse and the angular momentum in relation to the drag created by the body, theoretically determine the velocity attained by the swimmer. It was hypothesized that the resistance moment

impulse developed in swimming training would constitute a training load which would be sufficient to develop muscle force and thus the applied force moment. The training stimulus would be similar to isotonic exercise. Thus, changes in impulse for the extended time period were expected. The stimulus for the initial time period was a combination of inertial and resistance loads. Velocity increases would be accompanied by acceleration decreases over the period so that inertial load would be exchanged for resistance load. It was hypothesized that the load within the leading edge time period would constitute a sufficient stimulus to develop the applied moment.

Swimming also depends upon the rate of work at which a swimmer performs throughout an event. The work output can be attributed to the change in the kinetic energy developed by the body segments during propulsion. It was hypothesized that physiological and biochemical changes as a result of swimming training would affect the availability of chemical and thus kinetic energy for the propulsive movements.

Criterion Variables

All criterion variables were measured at or from the starting angle.

Shoulder extension (starting angle 150°):

1. Peak static moment at the starting angle.
2. Impulse. Initial segment.
3. Impulse. Extended segment.
4. Work output. Extended segment.

Elbow extension (starting angle 70°):

1. Peak static moment at the starting angle.
2. Impulse. Initial segment.
3. Impulse. Extended segment.
4. Work output. Extended segment.

Factors

Four factors were used in the experiment:

1. Treatments. The sample was divided equally into an experimental and a control group. The training program was administered to the experimental group over the six week period.

2. Ability. Three ability levels, high, medium and low, were created on the basis of initial swimming ability so as to experimentally control what was considered a concomitant variable. All Ss were ranked on their initial 50 metre (m) swimming test and divided into three groups of 16. Each pair of Ss was then divided into the experimental or control group on a random basis (a coin toss).

3. Days. Three testing days, each three weeks apart over the six week training period, were the levels of the third factor.

4. Trials. Four trials per test were given on each testing day.

The number of testing days, tests and trials was largely determined by the time available for testing and the effects of the tests on the criterion variables. It was felt the six week training period with three sessions per week would be sufficient to produce a significant improvement in swim performance. Increasing the number of testing days would have increased the possibility of the tests causing development, and the changes would have been reflected in the criterion measures. The three testing days permitted the use of trend analysis. Time available for testing was restricted by the need for a minimum disruption of the training schedule. All four tests were considered necessary and the number of trials was adjusted to match the time available on the testing day.

Experimental Design

A multi-factor, mixed design with repeated measures was used (Lindquist, 1956, pp. 266-306). Each of the six subgroups was administered one of the

combinations of the A (Treatments) and B (Ability) factors. All combinations of the C (Days) and D (Trials) factors were administered to the subgroups. Thus comparisons of treatments for factors A and B were inter-subject and the comparisons for C and D were intra-subject.

APPARATUS

Description

The apparatus was designed to provide a resistance moment proportional to the square of the velocity. A rotary torque actuator (Roto Actuator, Model DS4-4) with a lever arm attached to one end of the axle was used to provide an hydraulically controlled load. Rotation of the axle caused a vane to produce a flow of fluid which was directed past the stator via two bi-directional valves (Figure 6). For static and calibration tests, the lever arm was positioned and both valves closed. In dynamic tests, a constant setting was used for the controlled-flow valve and the return-flow valve was opened fully. A vernier scale on the valve handle ensured a precise valve setting for all Ss.

For the dynamic tests, the hydraulic system consisted basically of a pump, a tube and a constriction in

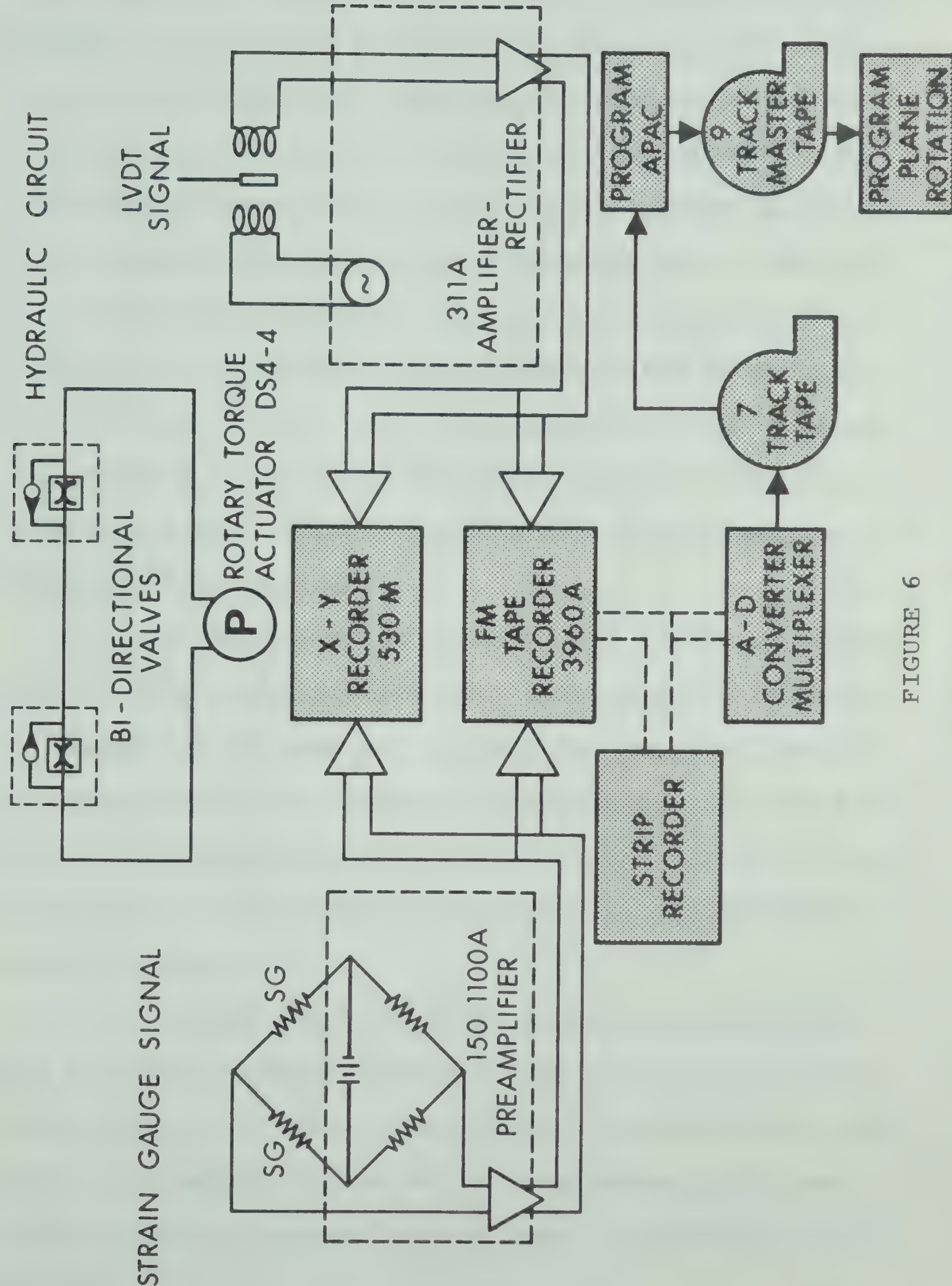

FIGURE 6

CIRCUIT DIAGRAMS

the tube. The flow of oil through the constriction as caused by moving the lever arm can be shown, by application of the momentum equation, to produce a resistance force proportional to the square of the velocity. The resistance moment acting on the vane depended on the fluid resistance and the fluid velocity was a function of the angular velocity. Thus, the resistance moment was similar to the resistance demonstrated by Seireg, Baz and Patel (1971). As the size of the constriction was under the control of the experimenter it was possible to select a flow rate which was appropriate for the response being tested.

The control valve setting used in the experiment was selected after preliminary tests on Ss in the same age range as the sample. The setting selected produced an interval for the shoulder effort which was judged by the E as approximating the period of arm stroke during propulsion. That setting was used for both movements and all trials.

A handle which could be adjusted to the width of the S's body segment (Figure 9) was positioned on the lever arm at a radius of 15.25 cm. The positioning was after preliminary trials of the apparatus. Felt and rubber blocks protected the Ss from the possibility of injury.

Bending strain for the lever arm was measured by a pair of strain gauges mounted near the axle. Angular displacement was measured by a Linear Voltage Differential Transformer (LVDT) firmly mounted below the axle (Figure 10). A cord from the core of the LVDT was taken over the axle and held by a pin screwed into the shaft. The linear range of the transducer (± 1 inch) adequately covered the angular displacements measured.

The bending strain and displacement signals were amplified, monitored on an X-Y recorder and recorded on an FM tape recorder (Figure 6). The strain gauge amplifier (Sanborn Carrier Preamplifier, Model 150-1100A) supplied an excitation voltage (4.5 volts), resistances for the remaining two arms of the Wheatstone Bridge, resistance and capacitance null balance controls and amplification. The LVDT amplifier (Sanborn Transducer Amplifier-Indicator, Model 311 A) produced an excitation voltage (2.4 kHz at approximately 5 v) and amplified and converted the output signal. The two recording systems were wired in parallel. Force and displacement were displayed on the axes of the X-Y recorder (Honeywell, Model 530M) which was used to monitor the responses, to check null balance and to determine the status of the system prior to each response. The signals were recorded on two of the four tracks available on the FM tape

recorder (Hewlett Packard, Model 3960 A). As the signal frequencies were low, a maximum of approximately 50 Hz, a slow tape speed was selected (15/16 in. per sec.).

Signal Conversion

The recorded signals were converted from an analog to a digital mode, by a process which involved two steps. Instrumentation for the conversion was supplied by the Technical Service department at the University of Alberta. The first step consisted of multiplexing the two channel input, performing analog to digital conversion and recording the output on two seven track magnetic tapes. The multiplexer alternately sampled the two input signals once every 20 msec. so that the sampling period for each channel was 40 msec. The alternating process produced an off-set time base which was realigned in the data analysis so as to give a common time base for the two signals. Preliminary examination of analog curves and examination of digital values for the curves showed the sampling frequency to be adequate, at least five datum points for the highest response frequency, the leading edge of the force signal. A 40 micro second gate was used, during which interval the analog signal was allowed to pass and was averaged. Digital records of 4096 bytes were recorded alternately on the two seven track tapes. The analog input was also displayed on a strip recorder.

Step Two consisted of composing a master nine track magnetic tape from the seven track tapes using the IBM 360/67 computer at the University of Alberta and a commercial program developed for the conversion process (APAC). The master tape consisted of alternating blocks of force and displacement values, 2048 entries per block, with each entry a half word (two byte) integer based on an arbitrary scale with zero as null and ± 3000 as full scale. As a check on the conversion process, curves composed from the digital data were viewed on a graphics terminal and found to compare favorably with the analog records.

Calibration

Force calibration consisted of moving the lever to a horizontal position, closing the valves and suspending weights from the handle. The weights were checked on a calibrated weighing scale. The digitized records of the calibration were printed and used for the relationships between moment of force and the arbitrary scale (Figure 7). For angular displacement calibration, a large protractor was mounted parallel to the plane of the lever arm. The two rotational axes were aligned, the base of the protractor levelled using a spirit level and the pointer of the protractor joined to the centre of the handle. The pointer was then aligned, through the degree

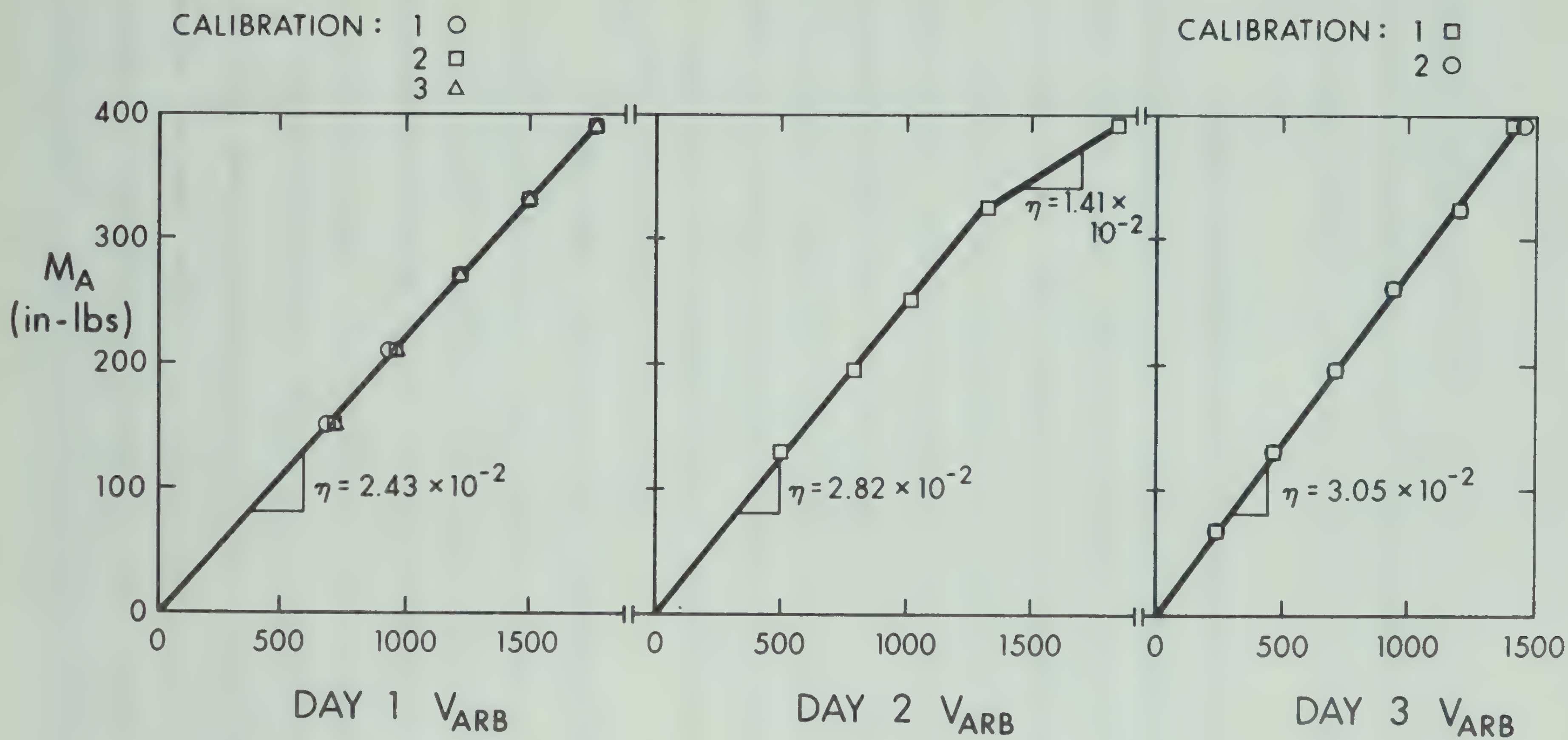

FIGURE 7

Applied Moment Sensitivities

marks, with a line on the centre of the lever arm. Relationships between angular displacement, in ten degree intervals, and the digitized records were graphed (Figure 8).

Units of measurement recommended by the Metric Practice Committee of the Canadian Standards Association (1970) were used. More specifically, the absolute metre (m), kilogramme (kg), second (s) system was adopted, with the unit of force, the newton (N), defined in terms of these units. Moment was measured as newton-metres (N.m) and plane angles as radians (rad). The calibrations involved the conversion of pounds force inches to newton-metres and degrees to radians (Figures 7 and 8). Impulse was measured as kilogramme metres squared per second ($kg.m^2/s$) and work as joules (J).

Instrument precision was evaluated just prior to the first testing day. Three calibrations over three days, for both force (Figure 7) and displacement, showed the relationships to be linear and variations in the slope to be virtually zero. The precision was checked statistically using analysis of variance to partition the variance into that due to replications of the calibration (days), inputs for each calibration and repetitions of each input (trials). The residual variance after removal of the variance due to inputs was effectively zero and gave a

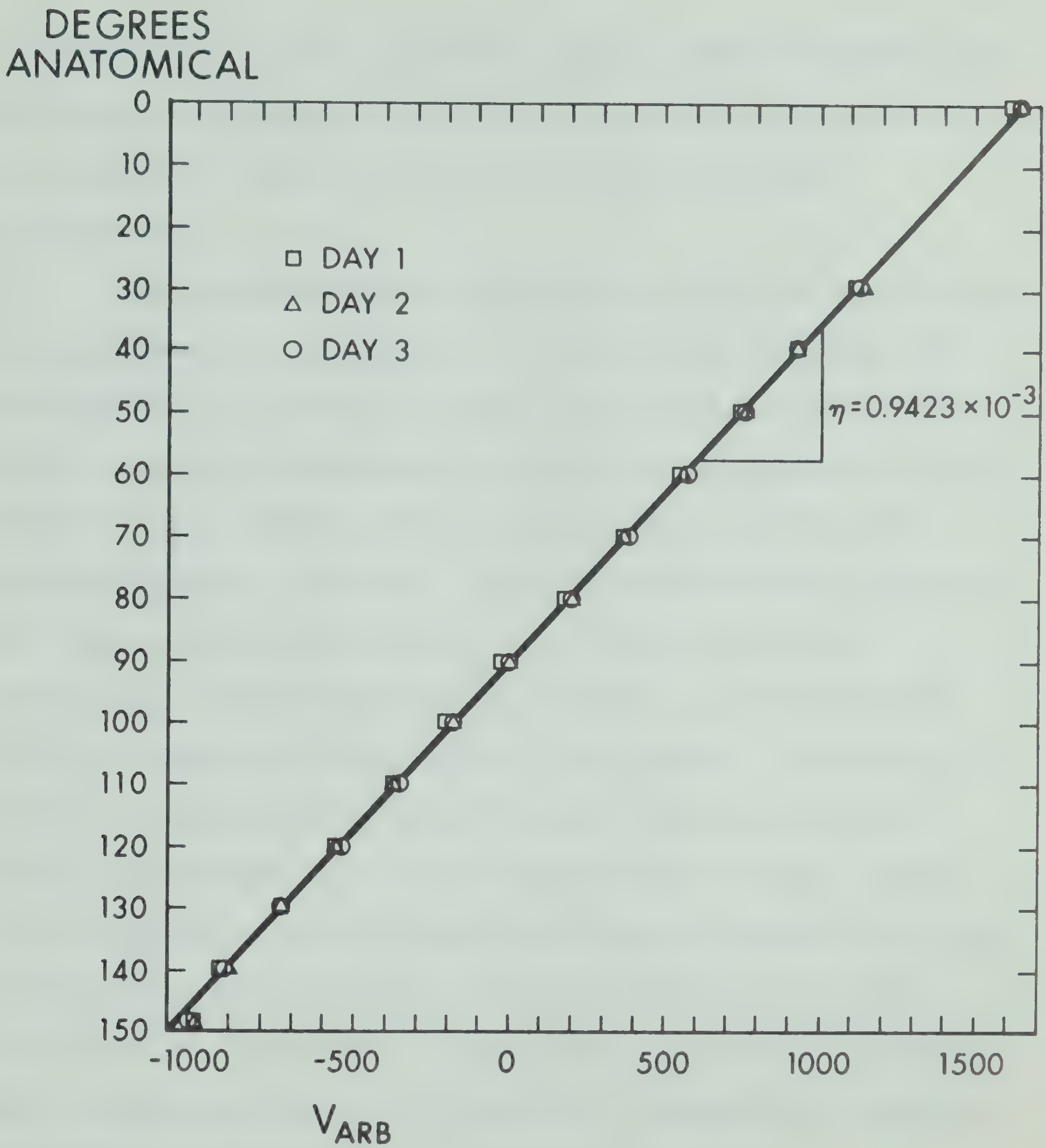

FIGURE 8

Angular Displacement Sensitivity

coefficient of 1.0. A further graphic check of precision for force was carried out on the third test day and showed a constant sensitivity over a 24 hour period (Figure 7).

Calibration sensitivities were recorded each test day and used in the analysis. Front panel settings and the warm-up period of 12 hours for the amplifiers, were held constant. Displacement sensitivities remained at the one level but sensitivities for the force calibration varied (Figures 7 and 8). As sensitivities were constant for each testing day and the sensitivity for that particular day was used in the analysis, the variations did not affect the validity of the results. It was found that for the second testing day the amplifier strayed into a non-linear portion of the amplifier range (Figure 7). Inspection of the digitized results showed that some of the shoulder responses were in the non-linear range. It was felt a bi-linear relationship would best describe the calibration points and would be comparatively easy to program.

METHOD

Testing

The laboratory tests and the swimming tests were held on consecutive days. The swimming tests were used to evaluate the effect of the training program on the

skill level and consisted of front crawl races over 25 m, 50 m and 100 m. A push-off start from the end of the pool was used to avoid problems with diving ability and performance was measured as the average of two timers per lane.

The laboratory tests were administered by subgroups. For the tests of shoulder extension, each _S_ in turn was positioned supine on the testing table with his shoulder level with the axis of rotation, arm inserted through the handle, knees flexed and soles of feet on the table (Figure 9). The shoulder harness was then adjusted to stabilize the position. Test instructions were given (Appendix B), an assistant stabilized the lower body by pressing down on the hips and the _S_ performed the four static contractions with approximately 30 seconds rest between responses. The control valve was then set to position three and the return valve fully opened to position ten, instructions given and the four dynamic responses tested. The rest period between the two tests was approximately three minutes and between the dynamic efforts, 30 seconds. _Ss_ were instructed to try and maintain the 120 degree angle at which the elbow was initially positioned for each trial. The bent arm represented the action about shoulder during swimming more effectively than a straight arm.

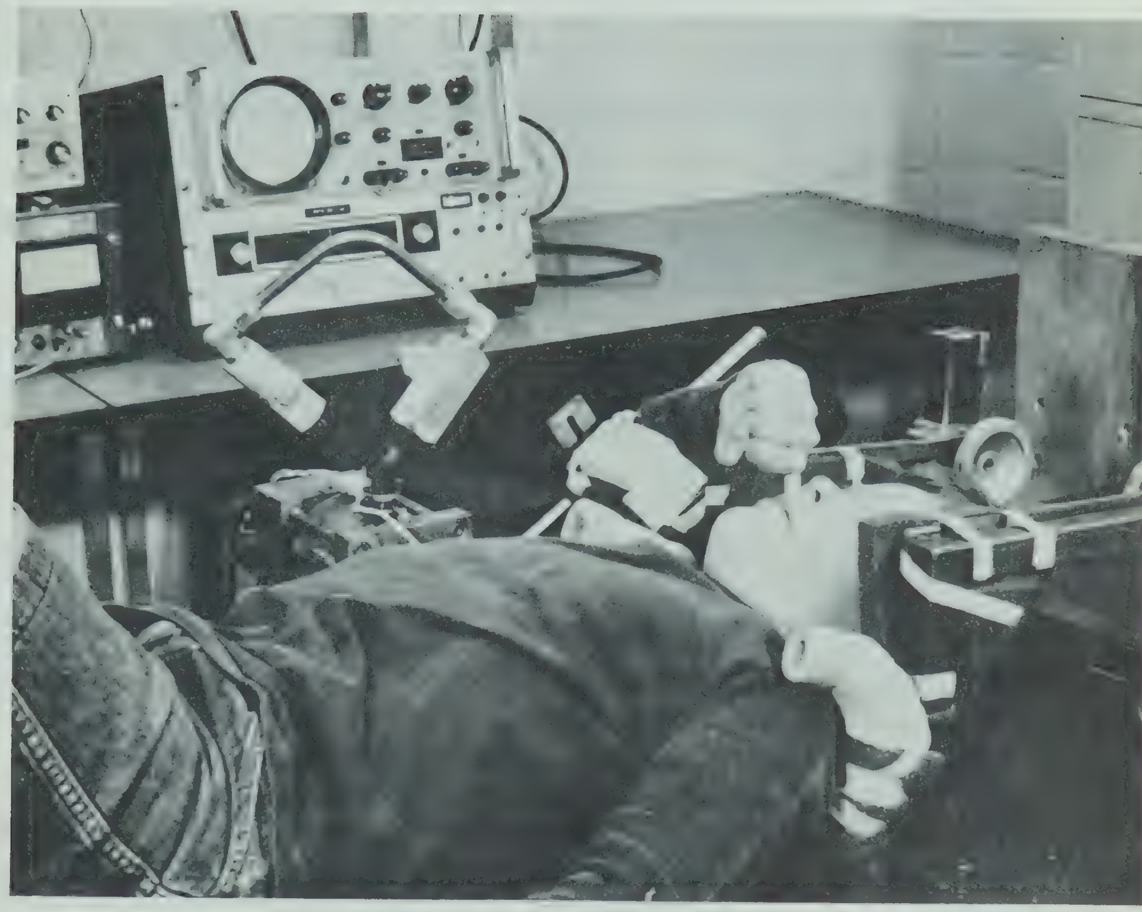

FIGURE 9

Testing Position for Shoulder Extension

The elbow extension tests were administered to the subgroups after the shoulder tests were completed. The procedure was similar, but with the elbow level with the axis of rotation, harness readjusted and the upper arm held down by the assistant (Figure 10). The total testing time for each subgroup was one hour.

Training

The training program was modelled on the practices used for age-group training. Front crawl was the only stroke used, however. Training distances ranged from 25 m to 1500 m with a balance being maintained between sprints and distance swims. Training sessions prior to testing days were restricted to light sprints.

Both the experimental and control groups were urged to avoid using the arms against heavy loads but otherwise to maintain normal play activities.

ANALYSIS

Arithmetic

A computer program using the Fortran IV G language under MTS control was written to calculate the criterion measures from the digital records (Appendix C). The output of the program matched the input requirements of the statistical analysis.

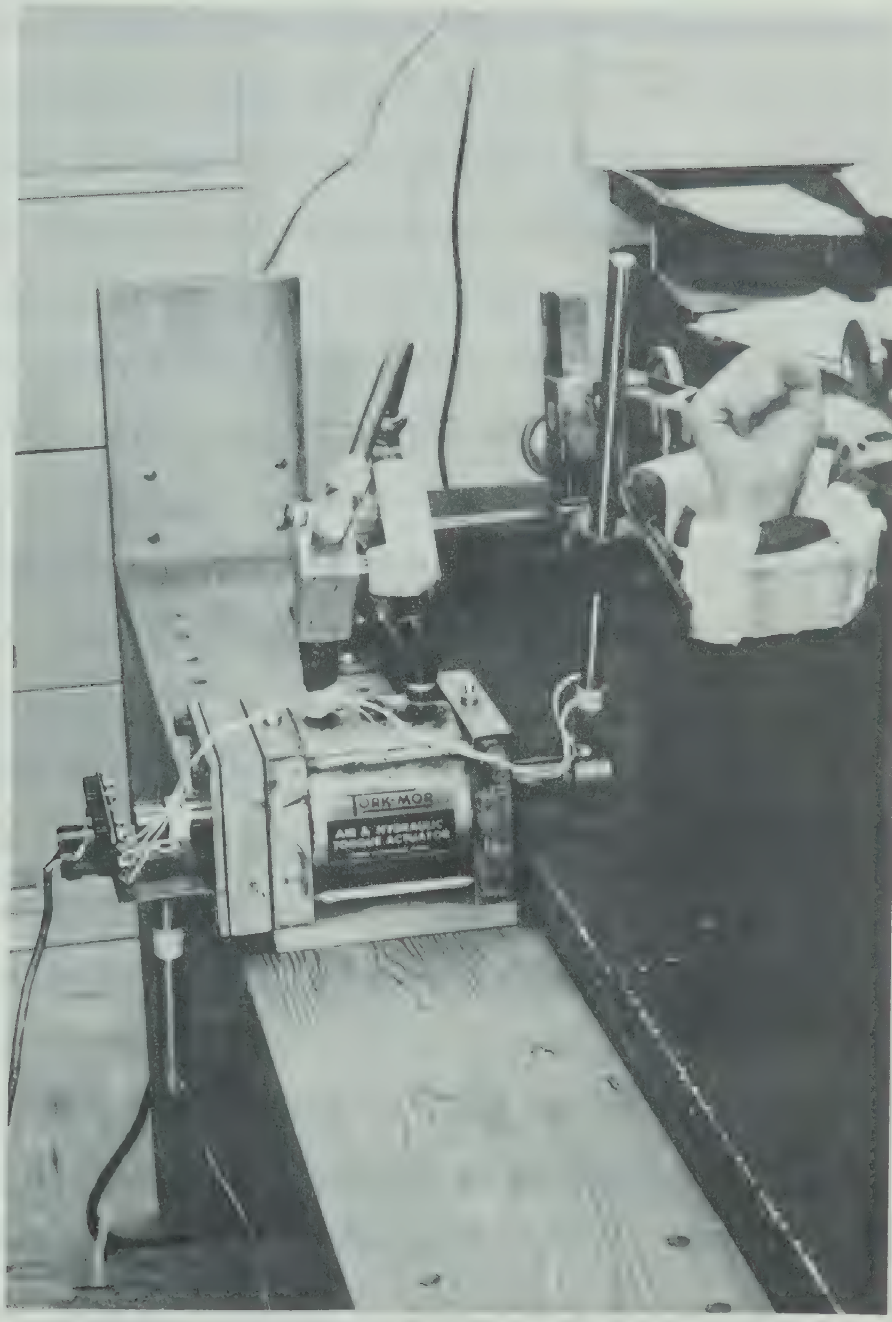

FIGURE 10

Testing Position for Elbow Extension

Parameter cards were used to select the segments of the records which contained the force/displacement data and to label these data. Use of a general trigger level in the program was not practical due to the noise created by preparatory activities and switching. Record segmentation was based on linear measures of the analog chart and checked from printouts of the master tape. The large memory requirements of the program made it necessary to calculate the criterion measures for each testing day in turn, enter the results in a disc file, concatinate the three files and then form the arrays for the statistical analysis.

The main steps in the program were:

1. Pairs of blocks were read, as required, and the data directed into arrays by the control cards. The first of each pair of blocks contained displacement data.

2. A subroutine (Peak) sorted the datum points for the static force tests to find the maximum value. These values were converted to newton-metres.

3. A criterion slope was used in the second subroutine (Areas) to locate the trigger point for the force curves. When three successive points with a slope greater than the criterion slope were found, the preceding point was set equal to zero and the values converted to newton-metres. The corresponding displacement values

were converted to radians and each pair of values averaged. The averaged values were taken as realigned with the time base for the force values.

4. A period of 0.4 second (ten datum points) was used for the initial segment of the impulse measures (Equation 5). The extended segment was 0.6 second (15 datum points) for elbow extension and 1.0 second (25 datum points) for shoulder extension. An integration subroutine based on Simpson's rule (Hildebrand, 1956, pp. 71-76) was taken from the IBM Scientific Subroutine Package (Subroutine QSF).

5. Work output (Equation 13) over the 0.6 second period for elbow extension and 1.0 second for shoulder extension was calculated using the trapezoidal rule subroutine (QTFG in the Scientific Subroutine Package) for a non-equidistant tabular function (Hildebrand, 1956, p. 75).

6. The values returned from the two sub-programs to the main program and subsequently printed were the results for the four trials, average of the trials and the peak trial, for each of the criterion measures. Average power over the four dynamic trials was also printed.

7. Arrays suitable for the statistical analysis were written on cards.

The criteria for the arithmetic analysis were based on examinations of the curves. The force curves showed a sharp transition from rest. A criterion slope just less than the least sensitive transition slope was used. The displacement curves were observed to be linear except for the initial acceleration period. These data, rather than the force data, were averaged because the linearity ensured a minimum deviation from the true values. Time limits for the dynamic tests were set after examination of the force curves. Elbow extension movements were of shorter duration than the shoulder movements. The data collection procedure made it logical to use a fixed time period and thus a variable displacement range for the limits of the work argument. A fixed displacement range would have necessitated interpolation of the datum points. The moment created by the weight of the lever arm and handle was adjusted for in the static analysis. Adjustments in the dynamic analysis would have further complicated the program for what was a very small proportion of the total moment of force.

Statistical

Homogeniety of the subjects within groups portion of within cell variance was checked using the Cochran Test (Winer, 1962, pp. 94-95, 321).

A two by three by three by four analysis of variance was used to test the hypotheses for the eight criterion measures (Winer, 1962, pp. 349-351). Levels for the four factors were selected according to systematic, non-random procedures and deemed fixed. A program for the four way analysis was not directly available. Between cell sum of squares were calculated using an N-way analysis of variance (ANOV 80) and within cell sum of squares were obtained by analyzing the experimental and control groups as separate experiments using a three way analysis with two factors repeated (ANOV 34) and summing the corresponding within cell terms. The programs were from the Department of Educational Research, University of Alberta.

In view of the level of precision used for the research there was a need to reduce the probability of a Type One error by using conservative tests in the analysis. Degrees of freedom for the terms which interacted with Ss were adjusted to make the tests more conservative (Winer, 1962, pp. 305-306, 321-322). A rejection level of 0.01 was set for the tests. The highly conservative Scheffe method was used *a posteriori* to test differences between means (Edwards, 1968, pp. 150-153). Descriptive statistics and the data required for homogeniety tests and comparison of means were obtained using Fortran programs written

specifically for the purpose.

The experimental design incorporated a reliability study based on the control group. Reliability was estimated by partitioning the variance into days, trials and _Ss_. Unbiased estimates of the components of variance were obtained using mean square values (Lindquist, 1956, Chapter 16; Gleser, Cronbach and Rajaratnam, 1956) from a three way analysis of variance (ANOV 80).

Tests were made of the hypotheses that training had no effect on swim performance over 25 m, 50 m and 100 m. These analyses were included to assist the interpretation of results and were not of primary concern in the study. A significance level of 0.05 for α was set for the tests. The factors, Treatments, Ability and Days, were analyzed using a three way analysis of variance with one factor repeated (ANOV 30).

The failure of one _S_ in the experimental group to complete the tests necessitated the removal of five other _Ss_. One _S_ from each of the remaining experimental subgroups was randomly removed and the three corresponding members of the control group were also removed from the analysis. Each subgroup was composed of seven _Ss_.

CHAPTER IV

ANALYSIS

Impulse and work output curves, derived arithmetically from the applied moment and angular displacement curves, were produced by the computer program. Each curve consisted of 25 datum points and the multiplicity of points made it necessary to select fixed, representative criterion points for the statistical analysis.

ARITHMETIC ANALYSIS

Two sets of curves, one each for shoulder and elbow extension, have been selected to illustrate the shapes of the curves (Figures 11 to 14). The sets were from different Ss and were recorded on the first testing day.

The angular displacement curves were similar to Figure 3 (Seireg, Baz and Patel, 1971). The set period over which the curves were recorded meant that the shoulder extension curves were terminated in the region of near constant velocity (Figure 11) but some of the elbow extension curves included the region of deceleration and the arrest of the lever arm by the table

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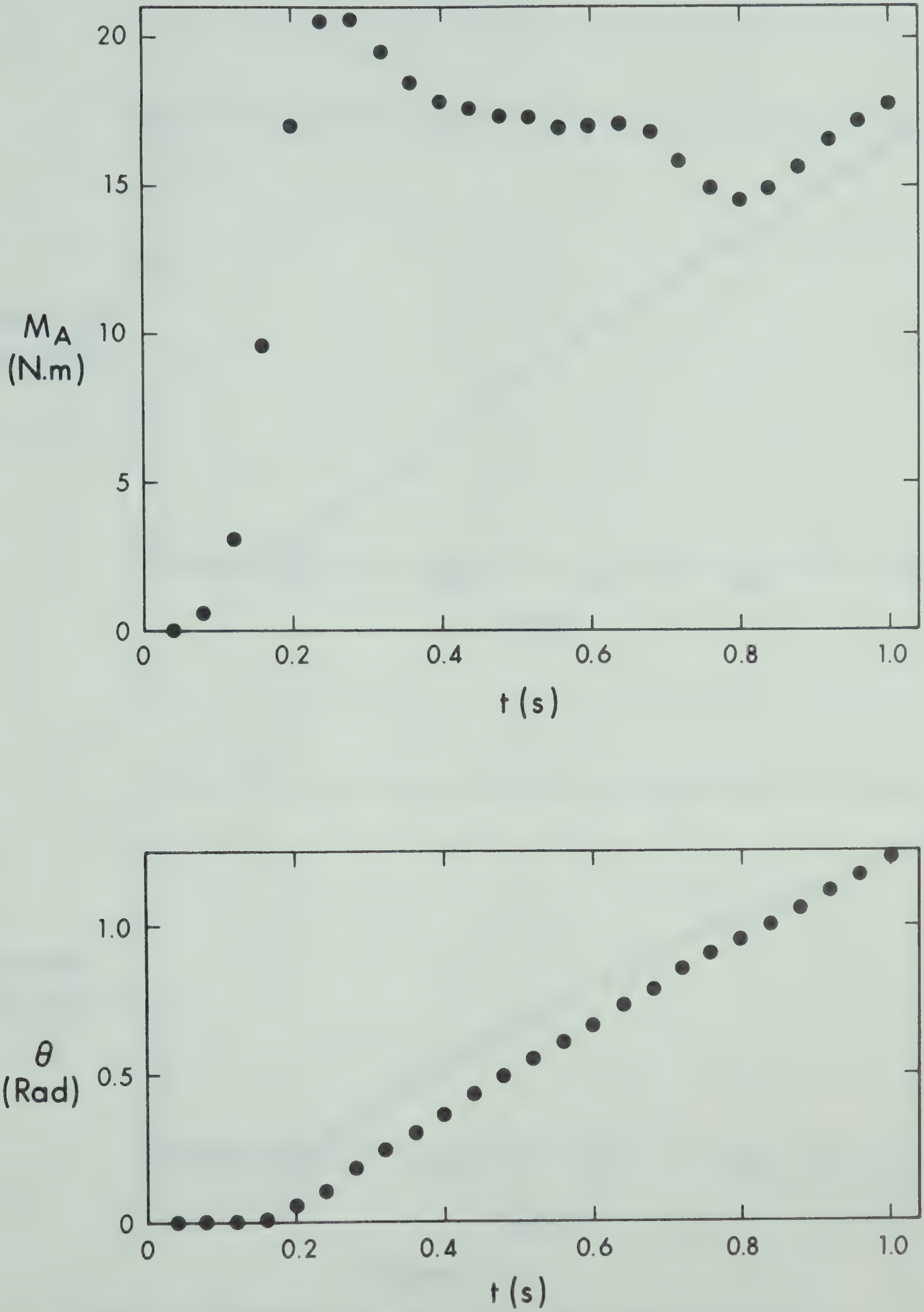

FIGURE 11

Shoulder Extension Applied Moment and Angular Displacement Curves

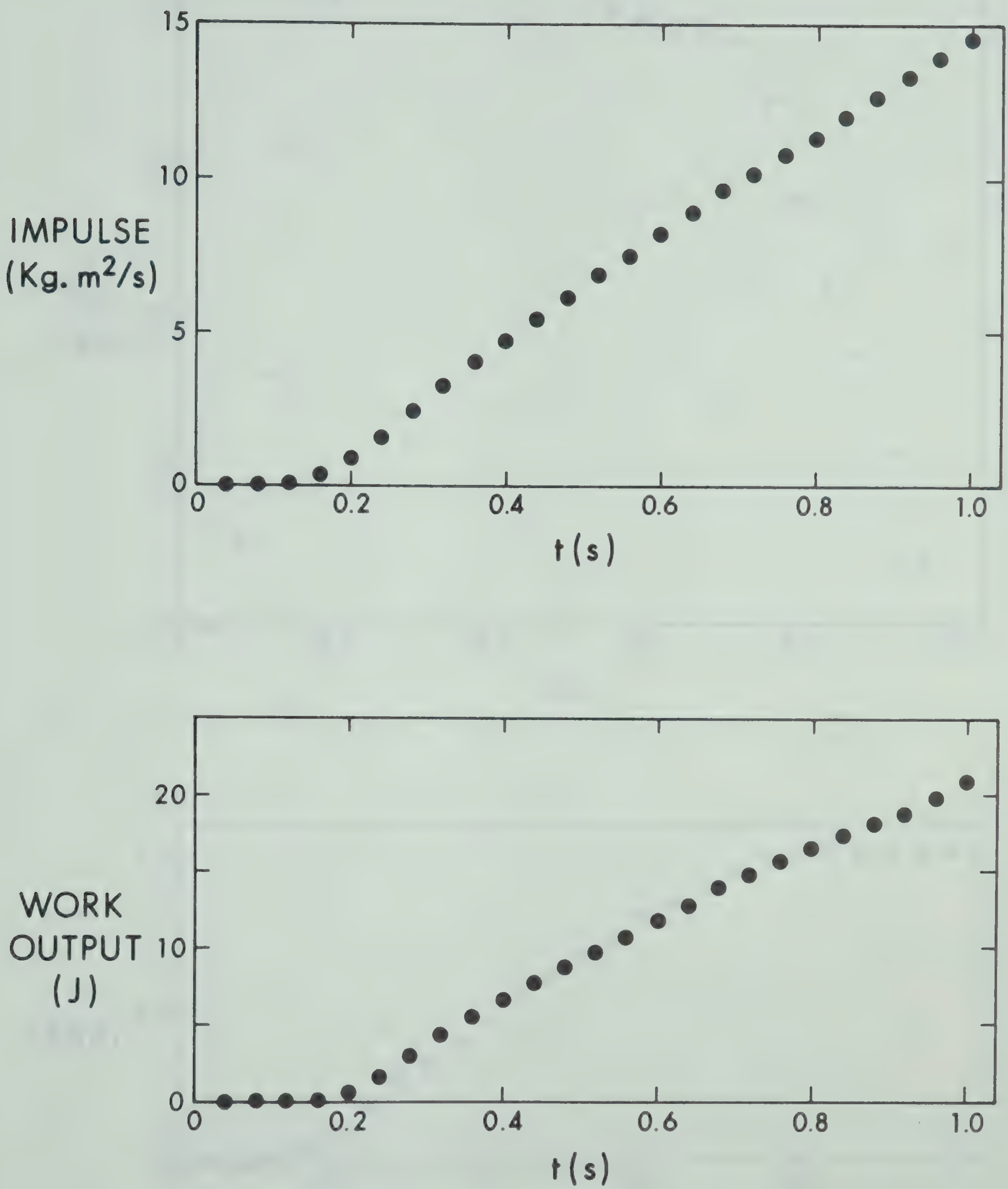

FIGURE 12

Shoulder Extension Impulse and Work Output Curves

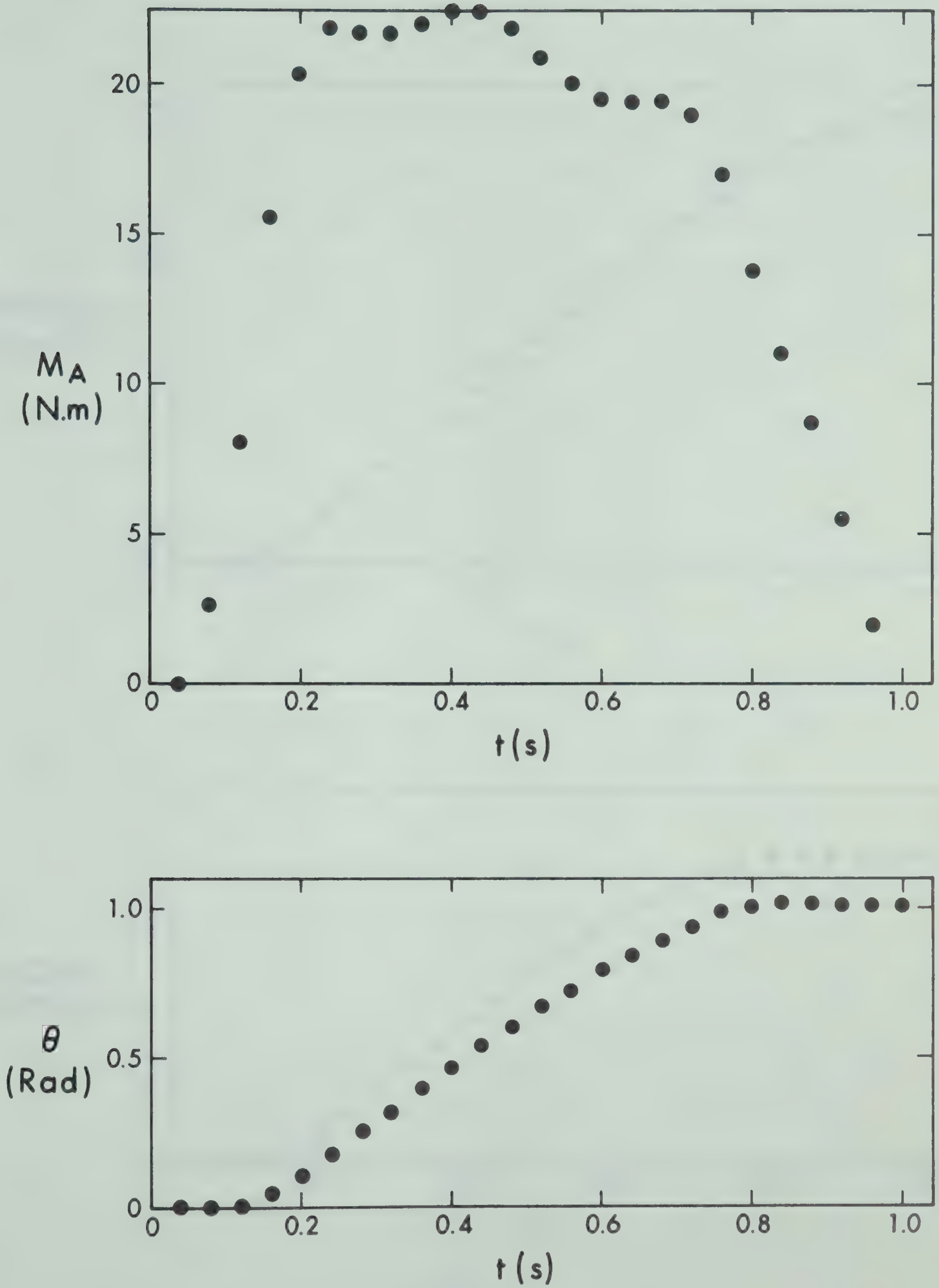

FIGURE 13

Elbow Extension Applied Moment and Angular Displacement Curves

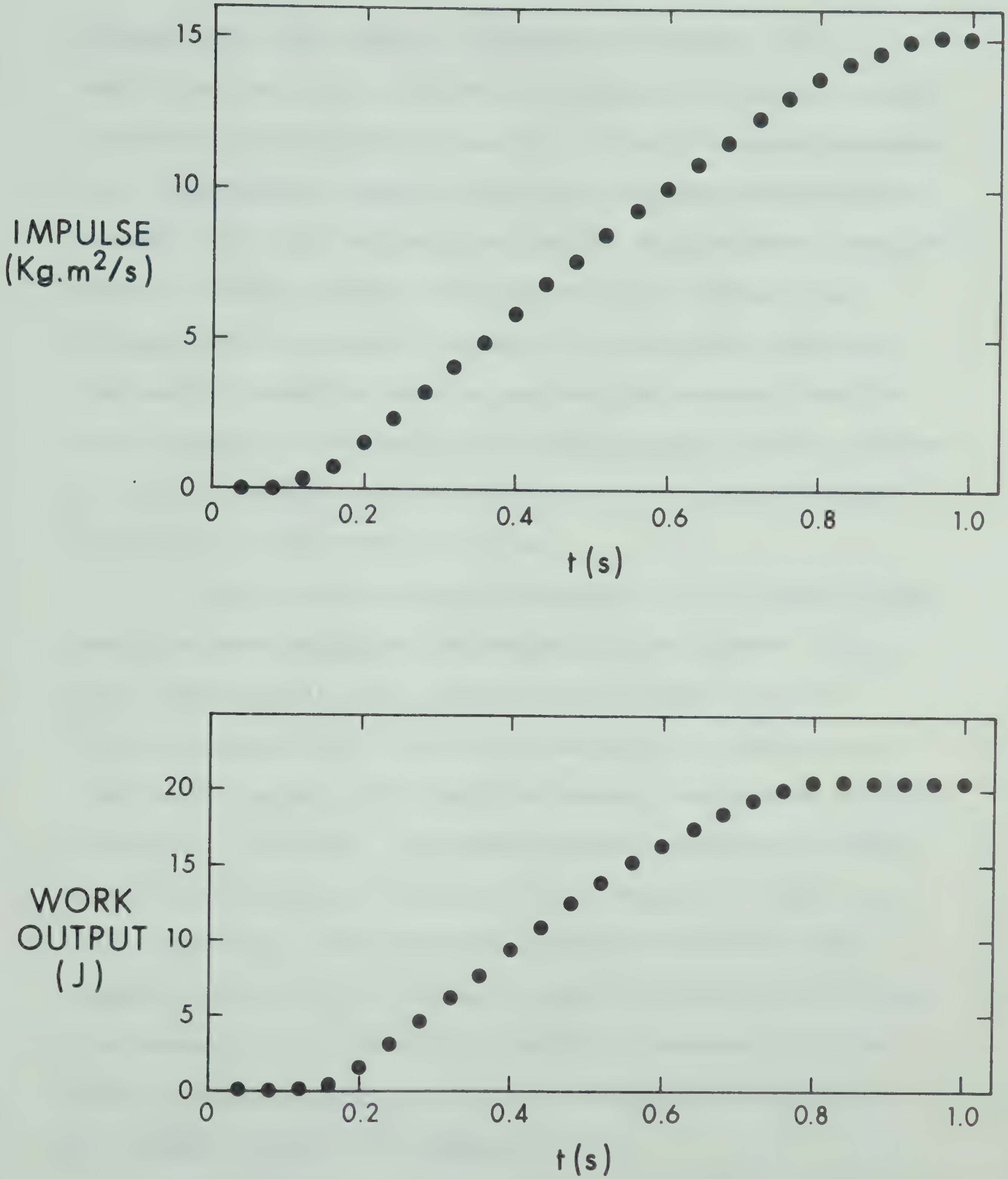

FIGURE 14

Elbow Extension Impulse and Work Output Curves

(Figure 13). The shape of the applied moment curve, a rapid rise in force followed by a period of near constant force, was anticipated (Page 40). The time interdependency of the applied moment and angular displacement curves showed that force was applied before displacement occurred. Static friction within the hydraulic and mechanical systems and the elastic element of the series elastic/ contractile model of muscle contraction account for the delay period. The impulse and work output curves (Figures 12 and 14) reflect the variations in the applied moment and angular displacement curves.

The criterion points selected for the statistical analysis were based on the shapes of the curves. The tenth datum point (0.4 second) was selected as the criterion point for the initial segment to ensure that the leading edge of all applied moment curves was included (Figures 12 and 14). Extended segment measures included the initial segment and part of the period of near constant velocity. The shoulder extension efforts were measured over the one second period (25 datum points) but the comparatively restricted range of movement for the elbow extension response made it necessary to select a 0.6 second period (15 datum points).

The mean and range of values for each of the criterion variables was as follows:

Shoulder static moment,	30.49	(11.61-55.55)	N.m .
Elbow static moment,	21.85	(10.45-39.14)	N.m .
Shoulder initial impulse,	4.706	(1.579-9.362)	$kg.m^2/s$.
Elbow initial impulse,	5.088	(2.329-9.239)	$kg.m^2/s$.
Shoulder extended impulse,	16.03	(6.99-25.86)	$kg.m^2/s$.
Elbow extended impulse,	9.09	(4.12-15.00)	$kg.m^2/s$.
Shoulder work output,	25.72	(2.77-61.94)	J .
Elbow work output,	13.23	(0.90-30.97)	J .

The extreme range of the shoulder extension and elbow extension work output values is attributable to the method of selecting the initial datum point. Individuals with little available force required a longer period to produce displacement and recorded smaller displacement increments than those with superior force.

STATISTICAL ANALYSIS

The analysis was designed to test the effect of the six week swim training program on the criterion measures and to see if the criterion measures were different for the three levels of initial swimming ability. Tests of the remaining factors and interactions were primarily of interest in evaluating the testing technique and were treated *post hoc*.

HYPOTHESES

For each of the eight criterion measures:

1. Administering the six week swim training program will not affect the performance of the experimental group in relation to the control group.

1a. H_1: $\sigma^2_{\alpha\gamma} = 0$

H_2: $\sigma^2_{\alpha\gamma} > 0$

1b. H_1: $\sigma^2_{\alpha\beta\gamma} = 0$

H_2: $\sigma^2_{\alpha\beta\gamma} > 0$

In the event that $\sigma^2_{\alpha\gamma} > 0$

1c. H_1: $\mu_{1.1.} = \mu_{1.2.} = \mu_{1.3.}$

H_2: $\mu_{1.1.} < \mu_{1.2.} < \mu_{1.3.}$

1d. H_1: $\mu_{2.1.} = \mu_{2.2.} = \mu_{2.3.}$

H_2: $\mu_{2.1.} \neq \mu_{2.2.} \neq \mu_{2.3.}$

1e. H_1: $\mu_{1.1.} = \mu_{2.1.}$

H_2: $\mu_{1.1.} \neq \mu_{2.1.}$

1f. H_1: $\mu_{1.2.} = \mu_{2.2.}$

H_2: $\mu_{1.2.} > \mu_{2.2.}$

1g. H_1: $\mu_{1.3.} = \mu_{2.3.}$

H_2: $\mu_{1.3.} > \mu_{2.3.}$

2. There is no difference in performance between the three initial swimming ability levels.

2a. H_1: $\sigma^2_{\beta} = 0$

H_2: $\sigma^2_\beta > 0$

2b. H_1: $\sigma^2_{\beta\gamma} = 0$

H_2: $\sigma^2_{\beta\gamma} > 0$

2c. In the event that $\sigma^2_\beta > 0$

H_1: $\mu_{.1..} = \mu_{.2..} = \mu_{.3..}$

H_2: $\mu_{.1..} > \mu_{.2..} > \mu_{.3..}$

2d. In the event that $\sigma^2_{\beta\gamma} > 0$

H_1: $\mu_{.1k.} = \mu_{.2k.} = \mu_{.3k.}$

H_2: $\mu_{.1k.} > \mu_{.2k.} > \mu_{.3k.}$

The direction given for the tests of differences between means was based on levels of, and expected changes in, swim performance.

RESULTS

Means and standard deviations of subgroups for each of the criterion variables are given in Appendix E, Tables 11 to 18. Calculated values for the Cochran test of the subjects within groups variance ranged from 0.204 to 0.416. At the 0.01 level, the critical value (Winer, 1962, p. 654) is:

$$C_{0.99}\ (6,6) = 0.487$$

The assumption of subjects within groups homogeniety of variance was justified.

The four way analyses of variance for the eight

[illegible]

criterion variables are summarized in Appendix D, Tables 3 to 10. In Table 1 the normal degrees of freedom, and the conservative degrees of freedom which were adopted for the analysis, are listed. As the study was exploratory, it was assumed that the covariance between pairs of observations for the levels of the repeated measures factors (Days and Trials) were not constant. Under these circumstances, it is more appropriate to use the conservative critical values.

Effect of Training

None of the interactions between Treatments and Days, and between Treatments, Levels and Days is significant at the 0.01 level of confidence with conservative degrees of freedom. Thus the null hypothesis cannot be rejected.

1a. H_1: $\sigma^2_{\alpha\gamma} = 0$

1b. H_1: $\sigma^2_{\alpha\beta\gamma} = 0$

Differences Between Ability Levels

The hypothesis of no difference between levels of Ability is rejected for three of the criterion measures; elbow extension impulse for the initial segment (Table 6: $F = 5.311$, $df_1 = 2$, $df_2 = 36$) shoulder extension work output (Table 9: $F = 5.847$) and elbow extension work output (Table 10: $F = 6.055$). The null hypothesis for

TABLE 1

CRITICAL F VALUES WITH CONSERVATIVE DEGREES OF FREEDOM

Source of Variation	Normal df	Conservative df	$F_{0.99}(df_1, df_2)$ (Conservative df)
Between Subjects			
A (Treatments)	1	1	7.35
B (Ability)	2	2	5.25
AB	2	2	5.25
Subjects w. groups	36	36	
Within Subjects			
C (Days)	2	1	7.35
AC	2	1	7.35
BC	4	2	5.25
ABC	4	2	5.25
C x subj. w. groups	72	36	
D (Trials)	3	1	7.35
AD	3	1	7.35
BD	6	2	5.25
ABD	6	2	5.25
D x subj. w. groups	108	36	
CD	6	1	7.35
ACD	6	1	7.35
BCD	12	2	5.25
ABCD	12	2	5.25
CD x subj. w. groups	216	36	

interaction between Levels and Days cannot be rejected for any of the criterion measures.

The comparisons of treatment sums for criterion measures with significant differences between levels of Ability are summarized in Appendix F, Tables 19 to 21. The differences for elbow extension impulse for the initial segment are significant at the 0.01 level of α. Shoulder extension and elbow extension work outputs are significantly different between the first and third and the second and third levels of Ability.

Reliability

The effects of trials and days on intra-individual variations were estimated in the reliability study. Variance components were estimated from the mean squares for days, trials and subjects in accordance with the procedure of Gleser, Cronbach and Rajaratnam (1956) and expressed as percentages of total variance (Appendix H, Tables 34 to 41). The negative components calculated indicated a zero or small positive variance in the generalization universe and were expressed as zeros. Percentages for the variance components due to differences in Ss over days ($\sigma^2_{\alpha\gamma}$) were large but variances due to differences over trials were small ($\sigma^2_{\beta\gamma}$). Reliability

coefficients were calculated for the A-true values and the B-true values (Lindquist, 1956, pp. 380-381). The correlation for different A-true values, with the values taken over an infinite number of B categories (trials) within the same A category (day), was calculated from:

$$r_{\mu_{i1.}\mu_{i2.}} = \frac{\sigma^2_{\gamma}}{\sigma^2_{\beta\gamma} + \sigma^2_{\gamma}}$$

The correlation was referred to as the reliability coefficient for trials. The corresponding correlation for days was given by:

$$r_{\mu_{i.1}\mu_{i.2}} = \frac{\sigma^2_{\gamma}}{\sigma^2_{\alpha\gamma} + \sigma^2_{\gamma}}$$

Coefficients for trials and days are listed in Table 2. The coefficients are estimates of the maximum reliability for mean values based on observations from a single A or B category.

<u>Effect of Training on Swim Performance</u>

The analyses of variance for swim performance over 25 m, 50 m and 100 m are presented in Appendix G,

TABLE 2

RELIABILITY COEFFICIENTS FOR TRIALS AND DAYS

Criterion Measure	Trials Coefficient	Days Coefficient
Static Moment - Shoulder	0.924	0.591
Static Moment - Elbow	0.919	0.690
Initial Seg. Impulse - Shoulder	0.768	0.514
Initial Seg. Impulse - Elbow	0.986	0.578
Extended Seg. Impulse - Shoulder	0.914	0.606
Extended Seg. Impulse - Elbow	0.963	0.594
Work Output - Shoulder	0.922	0.715
Work Output - Elbow	0.951	0.698

Tables 31 to 33. It was hypothesized that for each of the criterion measures, there is no interaction between Treatments and Days. These hypotheses were rejected at the 0.05 level of α with conservative degrees of freedom. The Treatments by Days Summary Tables (Appendix G, Tables 31 to 33) show the interaction effects are due to the changes in swimming performance for the experimental group and tests of simple effects and comparisons of treatment sums were not considered necessary. Significant differences for main effects due to Ability were the result of the method of assigning Ss to groups and the differences due to Treatments and Days were attributed to the effects of the training program.

Extraneous Effect

With the exception of work output for elbow extension, the effect across Days for each of the four way analyses of variance for the eight criterion variables (Appendix D, Tables 3 to 10) was significant. The significant F ratios, with degrees of freedom of 1 and 36, were shoulder extension moment 22.041, elbow extension moment 8.524, shoulder initial impulse 9.938, elbow initial impulse 9.582, shoulder extended impulse 9.514,

elbow extended impulse 9.674 and shoulder work output 8.247. As the interactions between Days and Treatments were not significant, the significant effects were due to an extraneous factor or factors not taken into consideration in the experiment. Comparisons of treatment sums for Days are given in Appendix F, Tables 22 to 28. Differences for all three levels of the Days factor were significant for elbow extension moment, initial segment impulse and extended segment impulse. Differences between the first testing day and the remaining testing days were significant for each of the shoulder extension criterion variables.

The Trials factor was included to determine if performance changes across four trials. It was hypothesized that there would be no difference between trials. The null hypothesis was rejected for shoulder extension moment ($F = 12.940$, $df_1 = 1$, $df_2 = 36$) and elbow extension work output ($F = 9.290$) (Appendix D, Tables 3 and 10). Means across trials are given in Appendix I. Comparisons were made of treatment sums for Trials (Appendix F, Tables 29 and 30). Performance decreased across Trials for shoulder extension moment, with the first trial significantly greater than the remaining three trials. Elbow extension work output increased across trials, with the first trial significantly less than the remaining trials

and the second trial less than the fourth trial.

DISCUSSION

Time interdependent applied moment and angular displacement curves revealed the major features of the responses tested. A delay period between the initial force application and the start of displacement was attributable to the static moment created by the apparatus and to the elastic element of muscle contraction. An extended period of near constant velocity was due to the resistance moment increasing with the square of angular velocity until a state of equilibrium was produced. That state was maintained for most of the movement range. The applied moment curves consisted of an initial sharp rise followed by the period of near constant force.

Results for swim performance showed that the training program was successful and produced the anticipated changes. The changes in swim performance were not accompanied by changes in the criterion measures however. There was no difference in performance between the experimental and control groups over the six week training period. As the training stimulus involved a large number of repetitions for both the shoulder extension and elbow extension movements, that aspect of the total

training load was considered adequate. It has been demonstrated by Thistle, Hislop, Moffroid and Lowman (1966) that high resistance training over an eight week period produces increases in measures of the type used in this study. It would appear from the above that the resistance which develops during front crawl swimming training is not sufficient to increase the rotational force for the shoulder extension and elbow extension movements. This conclusion has to be related to the reliability study however. It was demonstrated that variance due to differences in Ss over days was high. This would be expected to affect the interactions tested in the main study (Hypotheses 1a, 1b).

The significant differences between levels of Ability, for elbow extension initial segment impulse and work output for shoulder extension and elbow extension indicate that there are differences in rotational force for groups based on initial swimming ability. These differences are not attributable to the training program however and describe differences between the three populations sampled under the Ability factor. The reason or reasons for these differences could be used as the basis of a further study. The results of the present investigation suggest that the three criterion measures which are significantly

different would be the logical variables to use in such a study. If the investigator was prepared to accept a 0.05 level of α however, all criterion measures, with the exception of initial segment impulse for shoulder extension, are significant. These differences indicate that the criterion measures selected were valid for the skill of front crawl swimming speed and further study of their relative merit is warranted.

The presence of a significant Days factor was not anticipated. The nature of the factor is unknown but the results indicate that some form of learning occurs. Further investigation of these changes is needed. The complexity of the testing situation, particularly for the dynamic efforts, may make it necessary to use a training period to familiarize the S with the apparatus. Additional support for the S such as straps and clamps, may also be needed.

Reliability for trials was, with the exception of shoulder extension initial segment impulse, adequate. There were no significant differences between trials for six of the eight criterion measures. The use of a familiarization period would be expected to further reduce the subjects by trials variance estimates and the between trials variance.

Within the experimental restrictions of the study

the implications for competitive swimming are as follows:

1. Swimming training of the type used in the study does not improve the rotational force for shoulder extension and elbow extension.

2. There is a relationship between level of swimming ability and rotational force.

If the premise that improvements in force are necessary for the production of high levels of swim performance is accepted, some means of developing rotational force must be used to supplement swimming training. This argument could be used as the basis for a further study of the relationship between swim performance and rotational force.

CHAPTER V

SUMMARY AND CONCLUSIONS

SUMMARY

The purpose of the study was to present and evaluate a system of biomechanical force measures. Constrained, noncentroidal, plane rotation of a rigid body was used as the model for the system. Rotational force measures appropriate to the skill of front crawl swimming speed were selected as criterion variables and used to evaluate the system. The experiment was designed to see if the criterion variables differentiate between levels of swimming ability and change as a result of swimming training.

The steps in the system and the corresponding decisions for the swimming study were:

1. Selection of the skill. The stimulus produced by fluid forces during front crawl swimming training was considered sufficient to develop muscle force.

2. Analysis of the skill into component body segment rotations. The primary movements for front crawl swimming were judged on the basis of related literature and a segmental analysis, to be shoulder

[illegible]

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[illegible]

[illegible]

[illegible]

[illegible]

extension and elbow extension.

3. Selection of derived force measures appropriate for the skill. The load against which the arm segments act during front crawl swimming is essentially a velocity sensitive resistance moment. The measures used were of the moment applied against such a load. The derived force measures used as criterion variables were peak static moment at the starting angle, impulse for the dynamic response over the initial time period (when force was increasing), impulse over an extended time period covering most of the force application, and work output over the extended period, for both of the selected movements. These measures were justified in terms of the related literature and principles of mechanics.

4. Evaluation of the skill. Front crawl swimming speed was tested over 25 m, 50 m and 100 m.

5. Evaluation of the selected body segment responses. A rotary torque actuator and a system of valves were used to provide a velocity sensitive resistance moment. Applied moment was calculated from the bending strain for the lever arm and angular displacement was calculated from the output of a LVDT activated by the shaft of the actuator. The lever arm paralleled the action of the body segment. The signals were digitized and then analyzed in a digital computer.

6. Manipulation of variables thought to affect the applied force patterns. Half of the sample of beginning competitive swimmers, eight to eleven years, was administered a six week period of swimming training.

7. Re-evaluation of the skill and the body segment responses. Swimming speed and the criterion variables were re-evaluated after the experimental group had completed three weeks and six weeks of training. The experimental design consisted, essentially, of a Treatments factor and a (testing) Days factor. A third factor, Ability, was added to divide the Treatments groups on the basis of swimming ability and to permit comparisons between levels of ability. The fourth factor, Trials, permitted comparisons between the four trials administered for each response.

The hypotheses of no interaction between Treatments and Days and between Treatments, Ability and Days could not be rejected at the 0.01 level of α with conservative degrees of freedom. The absence of improvement in the experimental group was attributed to the resistance for each segment rotation being too small to act as a training stimulus. As swimming speed increased significantly, some variable other than changes in the mechanical responses considered basic to the skill must have produced the change.

Differences between levels of Ability, for elbow extension initial segment impulse and work output for shoulder extension and elbow extension, were significant. The reasons for the differences were not attributable to the study. With a less conservative level of significance, 0.05 for α, F ratios for seven of the eight criterion measures were above the critical value. These results were taken as indicating the criterion measures selected were meaningful for the skill of front crawl swimming speed.

Improvements in the testing techniques are necessary. A significant Days factor and low reliability across days indicated that a pre-testing familiarization session is necessary to reduce learning effects and intra-individual variance. Additional support for the S may also be needed. A study of the effects of these changes is required. Apparatus precision was shown to be high and reliability across trials was adequate.

As swimming training did not provide an adequate training stimulus for the criterion measures used in the study, only a partial evaluation of the system of bio-mechanical force measures is possible. The measures differentiate between levels of swimming ability. A preliminary step is needed to re-approach the question of relating changes in swimming speed and changes in the criterion measures. It is suggested that a study be made

of the effect of high resistance training, using isokinetic or isotonic principles and the load provided by the hydraulic device, on the criterion variables used in the present investigation. With the general principles thus established, a study could be made of the effect on swimming speed of supplementing swimming training with resistance training.

Complete evaluation of the system of standardized biomechanical force measures is an on-going process. Other skills have to be selected and analyzed, appropriate criterion measures devised and effective methods of developing the force patterns used. The present investigation suggests that with the possible exception of activities such as wrestling and weight lifting, the load produced by the skill could be inadequate as a training stimulus for transient force variables. It is suggested that in further study of the relationship between skills and standardized biomechanical force measures the effect of supplementing skill training with resistance training should be investigated.

CONCLUSIONS

A system for relating biomechanical force measures to physical education skills was presented.

An evaluation of the system was made by applying it to the skill of front crawl swimming speed. Within the

delimitations of the study and the limitations of the design and testing techniques the following conclusions were drawn:

1. A six week training session for beginning competitive swimmers does not affect the criterion variables selected for the study.

2. There are significant differences between levels of initial swimming ability for the following criterion variables; initial segment impulse for shoulder extension, work output for shoulder extension and work output for elbow extension.

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APPENDIX A

SEGMENTAL ANALYSIS OF FRONT CRAWL SWIMMING

Purpose

The purpose of the study was to examine variations in front crawl swimming speed during a cycle of the stroke and to relate these variations to shoulder and elbow extension movements.

Procedure

The segmental analysis was based on a section of "Swim Stroke Analysis," a film by James Councilman. An underwater, side view of a male swimmer was projected and the position of the estimated centre of gravity points for each body segment measured in terms of a set of fixed rectangular coordinates. The coordinates were based on a horizontal-vertical reference grid shown behind the swimmer. Every fifth frame was analyzed and a time period calculated in terms of a filming speed of 32 frames per second. The position of the whole body centre of gravity was estimated by equating the moment due to body weight with the sum of the moments due to segment weights. Segment weight proportions and linear dimensions were from Dempster (1955). A computer program using the APL language was written to calculate centre of gravity points and horizontal displacement and velocity for the centre of gravity. Angular displacements for shoulder extension were measured and angular velocity calculated. As elbow extension involved considerable movement in the

third dimension and the analysis was restricted to two dimensions, a quantitative analysis was not possible. The period of elbow extension was judged from the projected images.

Results

Average horizontal velocity for the centre of gravity and average angular velocity for shoulder extension over the time interval between frames are shown in Figure 11. If the variations in horizontal velocity are considered in terms of the fixed cylindrical model of Seireg, Baz and Patel (1971) the drag moment is proportional to angular velocity and the horizontal propulsive force is the horizontal component of the drag moment. It is evident from Figure 11 that in the middle range of the arm movements angular velocities are at a peak. In accordance with Newton's Second Law of Motion, horizontal acceleration would be expected to be maximal during these periods. Horizontal acceleration was effectively zero over the middle range of the arm movements, however. Acceleration occurred during the initial and final phases of the shoulder extension movement. During the initial phase the horizontal velocity and thus drag was comparatively small and horizontal acceleration could be attributed to the shoulder extension drag moment.

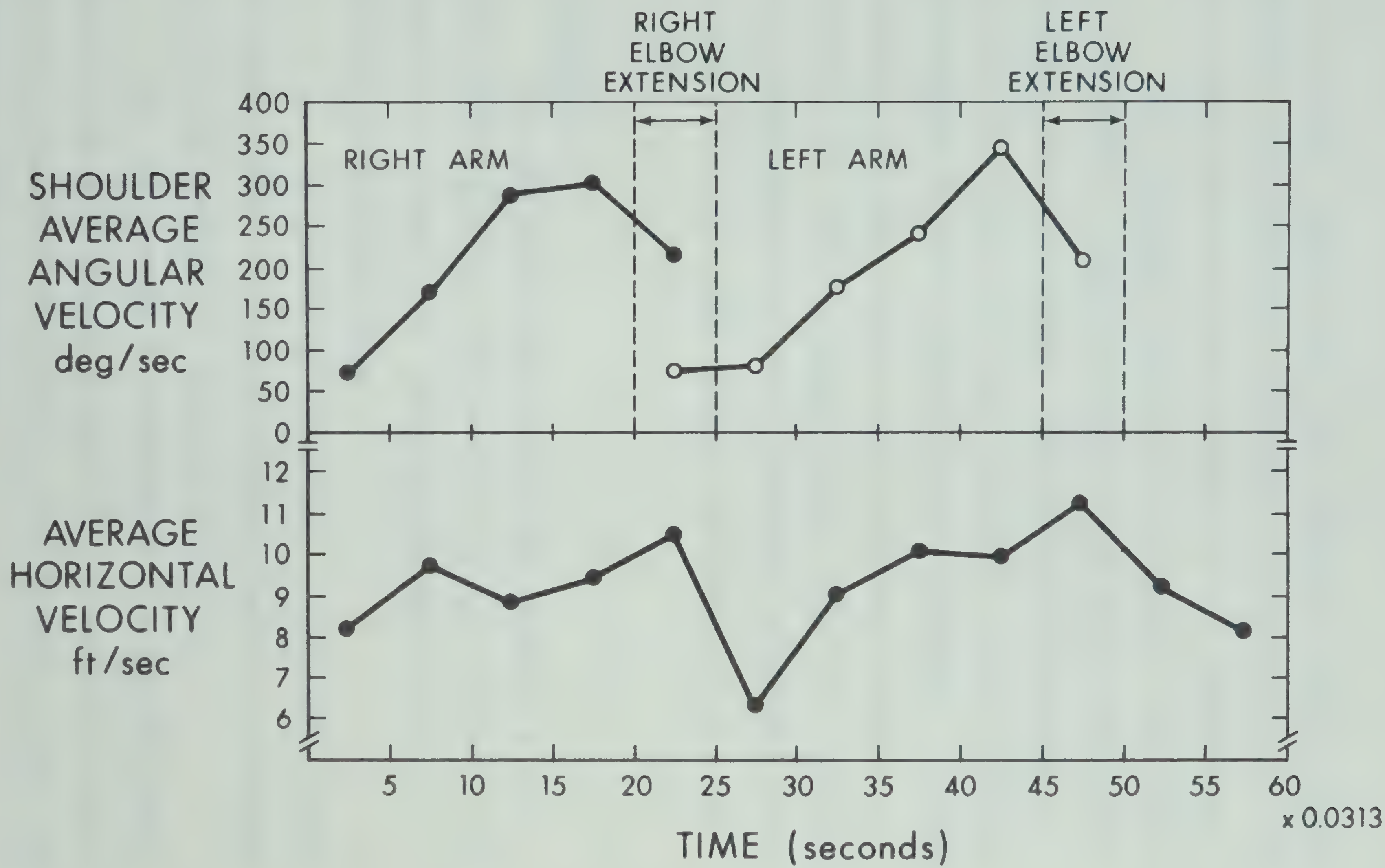

FIGURE 15

Relationship of Arm Segment Motions and Front Crawl Horizontal Velocity

It is evident however that the cylindrical model is inadequate for explaining variations in horizontal velocity during the middle and final phases of the arm movement.

The secondary increase of horizontal velocity can be attributed in general terms to the forces created by movements about the elbow. The period of horizontal acceleration during the final phase of the arm movement corresponded with the elbow extension movement. Cinematographic tracings indicate that the hand movement is directly back (Brown and Councilman, 1971) and the forearm is positioned to produce a maximum horizontal force component from the drag moment (Plagenhoef, 1971, pp. 122-124).

Conclusions

The following conclusions are based on a two dimensional segmental analysis of a single cycle of one competitive swimmer and are only intended to give guidance for further study.

1. The period of horizontal acceleration during the initial phase of the arm movement can be attributed to the force created by shoulder extension.

2. The period of acceleration during the final phase of the arm movement cannot be explained in terms of shoulder extension force but is attributable to the force produced by elbow extension.

APPENDIX B

TEST INSTRUCTIONS

The instructions given to the S prior to each test were as follows:

Static Tests

In this test you will not be able to move the lever. When told to do so you are to force against the lever as hard as possible and to continue exerting force until told to stop. The force you exert will be recorded.

Get ready, go.

Dynamic Tests

In this test the lever will move when you exert sufficient force against it. When told to do so, and not before, you are to force against the lever as hard as possible and to continue exerting force until the lever stops moving. Be sure that you are forcing against the lever as hard as possible at all times. The force you exert will be recorded.

Get ready, go.

APPENDIX C

COMPUTER PROGRAM

```
C     **********************PLANE ROTATION ANALYSIS*******************
C     ANALYSIS OF PLANE ROTATION OF SINGLE BODY SEGMENTS ABOUT A FIXED AXIS.
C     FORCE AND DISPLACEMENT TRANSDUCERS ARE USED TO MEASURE THE ROTATIONAL
C     MOVEMENT, AND  THE DIGITIZED RESULTS ANALYSED WITH THIS PROGRAM.
C     SEGNENTS ARE READ OFF TAPE AS DIRECTED BY CONTROL CARDS.
C     THE SEGMENTS CONTAINING THE RELEVANT SIGNAL ARE FORMED INTO ARRAYS.
C     ONE ARRAY (IDA) CONTAINS DISPLACEMENT MEASURES.
C     THE SECOND ARRAY CONTAINS FORCE MEASURES(IFA).
C     THESE MEASURES ARE IN ARBITARY INTEGER*2 UNITS WITH A MEAN OF ZERO
C     AND ARE INITIALLY RECORDED AS ALTERNATING BLOCKS ON THE TAPE.
C     SUBROUTINE PEAK IS CALLED TO DETERMINE THE HIGHEST VALUE IN A GIVEN FORCE
C     ARRAY. SUBROUTINE AREAS IS USED TO INTEGRATE FORCE/TIME AND FORCE/DISPLACE
C     -MENT CURVES.
C     THE RESULTS ARE THEN PRINTED AND/OR PUNCHED OUT.
      REAL*8 PKM(1,2,48),PKA(3,2,48,4),PK(1,2,48)
      DIMENSION II(192),JJ(192),KK(192),LL(192,8),NL(192,8),NN(4,48,4)
      REAL Z1A(3,2,48,4,25),Z2A(3,2,48,4,25),PKZ0(1,2,48),PKZ1(1,2,48)
      REAL PKZ2(1,2,48),Z0M(1,2,48),Z1M(1,2,48),Z2M(1,2,48),POW(1,2,48)
      INTEGER*2 ID(2048),IF(2048),IDA(2,48,4,150),IFA(4,48,4,150)
    8 FORMAT(3I3,3X,4F10.3,3X,F10.3,3X,F10.3)
C     NR=TOTAL NO. OF CARDS PER DAY, NS=TOTAL NO. OF S'S, IT=TOTAL NO. OF DAYS
C     TO BE ANALYSED IN THE PARTICULAR RUN.
    7 READ(5,13)NR,NS,IT
   13 FORMAT(I6,2I3)
      IF(NR.EQ.0)STOP
   26 MM=2048
C     2048 IS THE NUMBER OF ELEMENTS PER RECORD ON THE TAPE.
      DO 23 N=1,NR
      READ(5,27)II(N),JJ(N),KK(N),(LL(N,NI),NI=1,8),(NL(N,NI),NI=1,8)
   27 FORMAT(11I2,8I4)
C     CONTROL CARDS.
C     II=DAY
C     JJ=TYPE OF TEST.
C     KK=SUBJECT NUMBER.
```

```
C     LL=TRIAL NUMBER. TO BE GREATER THAN 4 IF NOT TO BE USED IN THE ARRAYS.
C     NL=ELEMENTS PER 'TRIAL' TO BE READ FROM THE TAPE.
      I=II(N)
      K=KK(N)
      J=JJ(N)
      DO 23 NI=1,8
      L=LL(N,NI)
      NM=NL(N,NI)
      IF(L.LT.5)NN(J,K,L)=NM
      DO 23 M=1,NM
      IF(MM.EQ.2048)READ(3)(ID(MM),MM=1,2048)
      IF(MM.EQ.2048)READ(3)(IF(MM),MM=1,2048)
      IF(MM.EQ.2048)MM=0
C     AS THE END OF THE RECORD IS REACHED THE NEXT RECORD IS READ.
      MM=MM+1
      IF(L.GT.4)GO TO 23
      IFA(J,K,L,M)=IF(MM)*(-1)
      IF(J.LT.3)IDA(J,K,L,M)=ID(MM)*(-1)
C     ARRAYS ARE FORMED.
   23 CONTINUE
      CALL PEAK(IFA,NN,I,NS,PKA,PKM,PK)
C     STATIC ANALYSIS OUTPUT.
      DO 6 J=3,4
      WRITE(6,5)
    5 FORMAT('-**MOMENTS OF FORCE** '/'DIMENSIONS',3X,'TRIALS',43X,'AVE'
     1,9X,'PEAK')
      DO 6 K=1,NS
      WRITE(1,8)I,J,K,(PKA(I,J,K,L),L=1,4),PKM(I,J,K),PK(I,J,K)
    6 CONTINUE
      CALL AREAS(IFA,IDA,I,NS,Z1A,Z2A,PKZ0,PKZ1,PKZ2,Z0M,Z1M,Z2M,POW,NN)
C     DYNAMIC ANALYSIS OUTPUT.
      DO 50 J=1,2
      IF(J.EQ.1)M=25
      IF(J.EQ.2)M=15
      WRITE(6,45)
```

```
   45 FORMAT('-*IMPULSE-INITIAL SEGMENT*'/'DIMENSIONS',3X,'TRIALS',43X,'
     1AVE',10X,'PEAK')
      DO 46 K=1,NS
      WRITE(1,8) I,J,K,(Z1A(I,J,K,L,10),L=1,4),Z0M(I,J,K),PKZ0(I,J,K)
   46 CONTINUE
      WRITE(6,48)
   48 FORMAT('-*IMPULSE-EXTENDED SEGMENT*'/'DIMENSIONS',3X,'TRIALS',43X,
     1'AVE',10X,'PEAK')
      DO 49 K=1,NS
      WRITE(1,8) I,J,K,(Z1A(I,J,K,L,M),L=1,4), Z1M(I,J,K),PKZ1(I,J,K)
   49 CONTINUE
      WRITE(6,52)
   52 FORMAT('-*WORK AND POWER*'/'DIMENSIONS',3X,'TRIALS',43X,'AVE',10X,
     1'PEAK',8X,'POWER')
      DO 53 K=1,NS
      WRITE(1,54)I,J,K,(Z2A(I,J,K,L,M),L=1,4), Z2M(I,J,K),PKZ2(I,J,K),PO
     1W(I,J,K)
   54 FORMAT(3I3,3X,4F10.3,3X,F10.3,3X,F10.3,3X,F10.3)
   53 CONTINUE
   50 CONTINUE
      STOP
      END
      SUBROUTINE PEAK(IFA,NN,I,NS,PKA,PKM,PK)
C     STATIC FORCE ANALYSIS.
C     CONVERSION OF ARBITARY UNITS TO REQUIRED UNITS, SELECTION OF THE PEAK
C     VALUE.
C     FORMATION OF ARRAYS FOR TRIALS AND THE CALCULATION OF THE MEAN AND THE
C     PEAK FOR THE FOUR TRIALS.
      INTEGER NN(4,48,4),P,FYA,FYB
      INTEGER*2 IFA(4,48,4,150)
      REAL*8 PKM(1,2,48),PKA(3,2,48,4),PK(1,2,48),LM
      READ(5,1)FS,FYA,FYB
    1 FORMAT(F7.6,2I6)
C     FS=CALIBRATION SLOPE(SENSITIVITY) FOR CONVERSION OF FORCE UNITS.
C     FYA=MOMENT DUE TO WEIGHT OF THE LEVER IN POSITION FOR TEST 3. INTEGER*2
```

```
C     UNITS.
C     FYB=MOMENT DUE TO LEVER, TEST 4. INTEGER*2 UNITS.
      DO 2 J=3,4
      DO 2 K=1,NS
      DO 2 L=1,4
      NM=NN(J,K,L)
      P=IFA(J,K,L,1)
      DO 2 M=1,NM
      IF(IFA(J,K,L,M).LT.P)GO TO 2
      IF(J.EQ.3)PKA(I,J,K,L)=((IFA(J,K,L,M)+FYA)*FS)
      IF(J.EQ.4)PKA(I,J,K,L)=((IFA(J,K,L,M)+FYB)*FS)
      IF(I.EQ.2.AND.IFA(J,K,L,M).GE.1275)PKA(I,J,K,L)=PKA(I,J,K,L)-(IFA(
     1J,K,L,M)-1275)*(FS-.014123)
      P=IFA(J,K,L,M)
    2 CONTINUE
      DO 4 J=3,4
      DO 4 K=1,NS
      PK(I,J,K)=PKA(I,J,K,1)
      LM=0.0
      DO 3 L=1,4
      LM=LM+PKA(I,J,K,L)
      IF(PKA(I,J,K,L).LT.PK(I,J,K))GO TO 3
      PK(I,J,K)=PKA(I,J,K,L)
    3 CONTINUE
      PKM(I,J,K)=LM/4.0
    4 CONTINUE
      RETURN
      END
      SUBROUTINE ARFAS(IFA,IDA,I,NS,Z1A,Z2A,PKZ0,PKZ1,PKZ2,Z0M,Z1M,Z2M,P
     1OW,NN)
C     DYNAMIC ANALYSIS TO CALCULATE IMPULSE AND WORK OUTPUT VALUES.
C     CONVERSION OF ARBITARY UNITS TO REQUIRED UNITS.
C     SELECTION OF A TRIGGER POINT FROM THE FORCE ARRAY(IFA).
C     FORCE AND DISPLACEMENT VECTORS BASED ON THIS POINT USED IN INTEGRATION
C     SUBROUTINES (SCIENTIFIC SUBROUTINES PACKAGE, I.B.M.).
```

```
C     FORMATION OF ARRAYS FOR TRIALS AND THE CALCULATION OF THE MEAN AND THE
C     PEAK FOR THE TRIALS. POWER OVER THE FOUR TRIALS CALCULATED FROM WORK
C     VALUES.
      REAL Z1(25),Z2(25),S(25),U(25)
      INTEGER DYA,DYB,NN(4,48,4)
      REAL Z1A(3,2,48,4,25),Z2A(3,2,48,4,25),PKZ0(1,2,48),PKZ1(1,2,48)
      REAL PKZ2(1,2,48),Z0M(1,2,48),Z1M(1,2,48),Z2M(1,2,48),POW(1,2,48)
      INTEGER*2 IDA(2,48,4,150),IFA(4,48,4,150)
      READ(5,7)INCF,H,FS,DS,DYA,DYB
    7 FORMAT(I5,5X,F6.4,2F7.6,2I6)
C     INCF=INCREMENT SELECTED TO FORM THE CRITERION SLOPE FOR THE TRIGGER POINT.
C       3 CONSECITIVE POINTS HAVING A SLOPE GREATER THAN THIS  ARE TAKEN AS THE
C     INITIAL POINTS OF THE CURVE TO BE INTEGRATED. INTEGER*2 UNITS.
C     H=TIME BASE BETWEEN POINTS IN THE ARRAYS. SECONDS.
C     FS=CALIBRATION SLOPE(SENSITIVITY) FOR CONVERSION OF FORCE UNITS.
C     DS=CALIBRATION SLOPE(SENSITIVITY) FOR CONVERSION OF DISPLACEMENT UNITS.
C     DYA=STARTING POSITION FOR DISPLACEMENT READINGS(CONVERTED TO ANGULAR UNITS
C    ) FOR TEST 1. INTEGER*2 UNITS.
C     DYB=STARTING POSITION FOR DISPLACEMENT READINGS(CONVERTED TO ANGULAR UNITS
C    ) FOR TEST 2. INTEGER*2 UNITS.
      DO 14 J=1,2
      DO 14 K=1,NS
      DO 14 L=1,4
      M=0
      NX=2
    8 M=M+1
      IF(M.EQ.NN(J,K,L))WRITE(6,1) I,J,K,L
    1 FORMAT(' ',4I3)
      IF(M.EQ.NN(J,K,L))GO TO 14
      IF(IFA(J,K,L,M+2).LT.IFA(J,K,L,M+1)+INCF.OR.IFA(J,K,L,M+1).LT.IFA(
     1J,K,L,M)+INCF)GO TO 8
      S(1)=0.0
      U(1)=0.0
    9 S(NX)=IFA(J,K,L,M)*FS
      IF(I.EQ.2.AND.IFA(J,K,L,M).GE.1275)S(NX)=S(NX)-(IFA(J,K,L,M)-1275)
```

```
    1*(FS-.014123)
     IF(J.EQ.1)U(NX)=(((IDA(J,K,L,M+1)+DYA)*DS)+((IDA(J,K,L,M)+DYA)*DS)
    1)/2.0
     IF(J.EQ.2)U(NX)=(((IDA(J,K,L,M+1)+DYB)*DS)+((IDA(J,K,L,M)+DYB)*DS)
    1)/2.0
     IF(NX.EQ.25)CALL  QSF(H,S,Z1,25)
     IF(NX.EQ.25)CALL  QTFG(U,S,Z2,25)
     IF(NX.EQ.25)GO TO 12
     NX=NX+1
     M=M+1
     GO TO 9
  12 CONTINUE
     DO 13 NX=1,25
     Z1A(I,J,K,L,NX)=Z1(NX)
     Z2A(I,J,K,L,NX)=Z2(NX)
  13 CONTINUE
  14 CONTINUE
     DO 20 J=1,2
     IF(J.EQ.1)M=25
     IF(J.EQ.2)M=15
     DO 20 K=1,NS
     PKZ0(I,J,K)=Z1A(I,J,K,1,10)
     PKZ1(I,J,K)=Z1A(I,J,K,1,M)
     PKZ2(I,J,K)=Z2A(I,J,K,1,M)
     AMZ0=0.0
     AMZ1=0.0
     AMZ2=0.0
     DO 18 L=1,4
     AMZ0=AMZ0+Z1A(I,J,K,L,10)
     AMZ1=AMZ1+Z1A(I,J,K,L,M)
     AMZ2=AMZ2+Z2A(I,J,K,L,M)
     IF(Z1A(I,J,K,L,10).GT.PKZ0(I,J,K))PKZ0(I,J,K)=Z1A(I,J,K,L,10)
     IF(Z1A(I,J,K,L,M).GT.PKZ2(I,J,K))  PKZ1(I,J,K)=Z1A(I,J,K,L,M)
     IF(Z2A(I,J,K,L,M).GT.PKZ2(I,J,K))  PKZ2(I,J,K)=Z2A(I,J,K,L,M)
  18 CONTINUE
```

```
      Z0M(I,J,K)=AMZ0/4.0
      Z1M(I,J,K)=AMZ1/4.0
      Z2M(I,J,K)=AMZ2/4.0
      POW(I,J,K)=AMZ2/(4.*M*H)
   20 CONTINUE
      RETURN
      END
```

APPENDIX D

ANALYSIS OF THE CRITERION VARIABLES

TABLE 3

FOUR WAY ANALYSIS OF VARIANCE

FOR SHOULDER EXTENSION STATIC MOMENT

Source of Variation	Conservative df	Mean Squares	F
<u>Between Subjects</u>			
A (Treatments)	1	414.680	0.900
B (Ability)	2	1839.593	3.995
AB	2	414.024	0.899
Subjects w. groups	36	460.523	
<u>Within Subjects</u>			
C (Days)	1	2815.268	22.041*
AC	1	213.362	1.670
BC	2	191.619	1.500
ABC	2	400.128	3.133
C x subj. w. groups	36	127.727	
D (Trials)	1	502.293	12.940*
AD	1	25.550	0.658
BD	2	44.430	1.145
ABD	2	30.866	0.795
D x subj. w. groups	36	38.816	
CD	1	34.734	0.742
ACD	1	82.268	1.757
BCD	2	32.865	0.702
ABCD	2	49.944	1.067
CD x subj. w. groups	36	46.814	

* Significant at the 0.01 level

TABLE 4

FOUR WAY ANALYSIS OF VARIANCE

FOR ELBOW EXTENSION STATIC MOMENT

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	53.139	0.245
B (Ability)	2	731.864	3.375
AB	2	137.163	0.632
Subjects w. groups	36	216.875	
Within Subjects			
C (Days)	1	567.789	8.524*
AC	1	60.219	0.904
BC	2	30.932	0.464
ABC	2	36.939	0.555
C x subj. w. groups	36	66.609	
D (Trials)	1	33.228	1.320
AD	1	14.785	0.587
BD	2	23.821	0.946
ABD	2	31.379	1.247
D x subj. w. groups	36	25.168	
CD	1	3.975	0.112
ACD	1	12.369	0.348
BCD	2	15.885	0.447
ABCD	2	38.074	1.072
CD x subj. w. groups	36	35.528	

* Significant at the 0.01 level

TABLE 5

FOUR WAY ANALYSIS OF VARIANCE FOR

SHOULDER EXTENSION INITIAL SEGMENT IMPULSE

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	25.961	2.569
B (Ability)	2	25.796	2.553
AB	2	11.444	1.133
Subjects w. groups	36	10.104	
Within Subjects			
C (Days)	1	46.218	9.938*
AC	1	1.761	0.379
BC	2	6.535	1.405
ABC	2	14.408	3.098
C x subj. w. groups	36	4.650	
D (Trials)	1	0.757	0.276
AD	1	2.389	0.872
BD	2	1.183	0.432
ABD	2	1.442	0.527
D x subj. w. groups	36	2.738	
CD	1	1.606	0.574
ACD	1	3.387	1.210
BCD	2	4.087	1.461
ABCD	2	1.756	0.627
CD x subj. w. groups	36	2.798	

* Significant at the 0.01 level

TABLE 6

FOUR WAY ANALYSIS OF VARIANCE FOR

ELBOW EXTENSION INITIAL SEGMENT IMPULSE

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	1.158	0.140
B (Ability)	2	43.883	5.311*
AB	2	2.576	0.312
Subjects w. groups	36	8.263	
Within Subjects			
C (Days)	1	37.013	9.582*
AC	1	0.650	0.168
BC	2	1.201	0.311
ABC	2	3.009	0.779
C x subj. w. groups	36	3.863	
D (Trials)	1	4.962	5.086
AD	1	0.621	0.636
BD	2	1.586	1.626
ABD	2	0.480	0.493
D x subj. w. groups	36	0.976	
CD	1	0.926	0.491
ACD	1	0.528	0.280
BCD	2	1.786	0.948
ABCD	2	1.656	0.878
CD x subj. w. groups	36	1.885	

* Significant at the 0.01 level

TABLE 7

FOUR WAY ANALYSIS OF VARIANCE FOR

SHOULDER EXTENSION EXTENDED SEGMENT IMPULSE

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	265.187	2.584
B (Ability)	2	444.117	4.328
AB	2	118.333	1.153
Subjects w. groups	36	102.623	
Within Subjects			
C (Days)	1	339.413	9.514*
AC	1	66.981	1.878
BC	2	35.770	1.003
ABC	2	100.768	2.825
C x subj. w. groups	36	35.674	
D (Trials)	1	5.591	0.458
AD	1	10.528	0.863
BD	2	9.131	0.748
ABD	2	3.836	0.314
D x subj. w. groups	36	12.199	
CD	1	17.277	1.370
ACD	1	11.201	0.888
BCD	2	15.439	1.224
ABCD	2	8.804	0.698
CD x subj. w. groups	36	12.609	

* Significant at the 0.01 level

TABLE 8

FOUR WAY ANALYSIS OF VARIANCE FOR

ELBOW EXTENSION EXTENDED SEGMENT IMPULSE

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	0.278	0.012
B (Ability)	2	120.443	5.105
AB	2	5.357	0.227
Subjects w. groups	36	23.592	
Within Subjects			
C (Days)	1	111.589	9.674*
AC	1	0.503	0.044
BC	2	3.408	0.295
ABC	2	11.250	0.975
C x subj. w. groups	36	11.534	
D (Trials)	1	12.057	5.045
AD	1	2.387	0.999
BD	2	3.972	1.662
ABD	2	1.434	0.600
D x subj. w. groups	36	2.390	
CD	1	2.505	0.575
ACD	1	0.925	0.212
BCD	2	4.618	1.060
ABCD	2	4.817	1.106
CD x subj. w. groups	36	4.356	

* Significant at the 0.01 level

[illegible]

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

TABLE 9

FOUR WAY ANALYSIS OF VARIANCE

FOR SHOULDER EXTENSION WORK OUTPUT

Source of Variation	Conservative df	Mean Squares	F
<u>Between Subjects</u>			
A (Treatments)	1	2084.234	2.340
B (Ability)	2	5207.521	5.847*
AB	2	1318.979	1.481
Subjects w. groups	36	890.701	
<u>Within Subjects</u>			
C (Days)	1	2019.926	8.247*
AC	1	548.142	2.238
BC	2	279.587	1.142
ABC	2	669.785	2.735
C x subj. w. groups	36	244.922	
D (Trials)	1	86.419	0.801
AD	1	90.284	0.836
BD	2	75.651	0.701
ABD	2	39.913	0.370
D x subj. w. groups	36	107.943	
CD	1	134.832	1.272
ACD	1	98.913	0.933
BCD	2	127.909	1.207
ABCD	2	86.617	0.817
CD x subj. w. groups	36	105.958	

* Significant at the 0.01 level

TABLE 10

FOUR WAY ANALYSIS OF VARIANCE

FOR ELBOW EXTENSION WORK OUTPUT

Source of Variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	6.943	0.034
B (Ability)	2	1250.478	6.055*
AB	2	98.923	0.479
Subjects w. groups	36	206.519	
Within Subjects			
C (Days)	1	384.293	5.725
AC	1	0.752	0.011
BC	2	37.755	0.562
ABC	2	107.408	1.560
C x subj. w. groups	36	67.140	
D (Trials)	1	206.870	9.290*
AD	1	23.155	1.040
BD	2	29.735	1.335
ABD	2	14.962	0.672
D x subj. w. groups	36	22.269	
CD	1	27.541	0.705
ACD	1	5.333	0.136
BCD	2	36.941	0.945
ABCD	2	34.596	0.885
CD x subj. w. groups	36	39.087	

* Significant at the 0.01 level

APPENDIX E

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

TABLE 11

SHOULDER EXTENSION STATIC MOMENT:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(NEWTON - METRES)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
a_1	b_1	M	32.00	34.87	34.25
		s	3.74	4.10	4.36
	b_2	M	31.75	34.67	36.47
		s	7.60	8.17	3.86
	b_3	M	23.18	28.11	27.28
		s	6.53	6.16	5.77
a_2	b_1	M	24.99	33.48	38.41
		s	5.55	9.89	8.78
	b_2	M	26.73	31.60	29.16
		s	6.31	5.43	9.94
	b_3	M	24.24	29.97	27.67
		s	4.83	6.36	3.90

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TABLE 12

ELBOW EXTENSION STATIC MOMENT :

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(NEWTON - METRES)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	22.01	23.70	22.14
		s	3.73	4.09	3.46
a_1	b_2	M	22.05	23.67	22.90
		s	5.22	5.90	3.99
	b_3	M	17.00	21.19	19.07
		s	2.63	5.26	3.17
	b_1	M	22.70	25.15	26.69
		s	5.06	7.83	5.19
a_2	b_2	M	20.27	22.56	21.84
		s	2.03	3.75	4.59
	b_3	M	18.47	21.45	20.46
		s	3.73	4.41	3.58

TABLE 13

SHOULDER EXTENSION INITIAL SEGMENT IMPULSE:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(KILOGRAMME METRES SQUARED PER SECOND)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	4.96	5.28	5.05
		s	0.93	0.65	0.82
a_1	b_2	M	5.02	5.35	5.88
		s	1.06	1.30	0.80
	b_3	M	3.80	4.52	4.53
		s	1.10	1.07	1.15
	b_1	M	3.72	5.05	5.73
		s	0.83	1.32	1.12
a_2	b_2	M	4.20	4.28	4.65
		s	1.10	0.91	1.50
	b_3	M	4.01	4.61	4.06
		s	0.99	0.73	0.60

TABLE 14

ELBOW EXTENSION INITIAL SEGMENT IMPULSE:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(KILOGRAMME METRES SQUARED PER SECOND)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	5.04	5.51	5.46
		s	0.43	0.53	0.39
a_1	b_2	M	5.14	5.34	5.30
		s	0.65	1.24	0.86
	b_3	M	3.96	4.99	4.61
		s	0.94	0.97	0.94
	b_1	M	5.08	6.05	6.00
		s	0.59	1.93	1.46
a_2	b_2	M	4.77	5.48	5.09
		s	0.76	0.60	1.18
	b_3	M	4.45	4.71	4.59
		s	0.78	0.44	0.68

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TABLE 15

SHOULDER EXTENSION EXTENDED SEGMENT IMPULSE:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(KILOGRAMME METRES SQUARED PER SECOND)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	17.60	18.49	17.58
		s	2.00	1.96	2.70
a_1	b_2	M	17.83	18.47	18.64
		s	3.07	4.59	3.05
	b_3	M	12.90	14.54	14.74
		s	3.05	2.76	3.04
	b_1	M	13.10	17.33	18.94
		s	2.14	4.61	3.04
a_2	b_2	M	14.29	14.77	15.48
		s	2.99	2.35	4.12
	b_3	M	13.51	15.38	13.96
		s	4.07	2.58	2.63

TABLE 16

ELBOW EXTENSION EXTENDED SEGMENT IMPULSE:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(KILOGRAMME METRES SQUARED PER SECOND)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	8.97	9.82	9.83
		s	0.59	0.95	0.71
a_1	b_2	M	9.25	9.58	9.59
		s	1.09	2.19	1.25
	b_3	M	7.16	9.07	8.33
		s	1.55	1.74	1.73
	b_1	M	8.97	10.62	10.39
		s	1.06	3.19	2.27
a_2	b_2	M	8.57	9.84	9.34
		s	1.29	1.12	1.88
	b_3	M	7.73	8.33	8.23
		s	1.58	0.70	1.25

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TABLE 17

SHOULDER EXTENSION WORK OUTPUT:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(JOULES)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	30.64	34.21	30.37
		s	6.60	6.49	8.06
a_1	b_2	M	31.65	33.41	33.75
		s	9.44	11.68	9.71
	b_3	M	16.57	18.64	20.56
		s	8.57	7.43	8.90
	b_1	M	19.03	29.62	34.33
		s	5.31	11.32	9.55
a_2	b_2	M	20.62	23.55	25.64
		s	8.43	7.01	11.88
	b_3	M	18.94	21.76	19.69
		s	12.23	8.21	7.48

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TABLE 18

ELBOW EXTENSION WORK OUTPUT:

MEANS AND STANDARD DEVIATIONS FOR SUBGROUPS

(JOULES)

TREATMENTS	ABILITY		DAYS C_1	C_2	C_3
	b_1	M	13.01	14.38	15.43
		s	2.17	3.10	2.64
a_1	b_2	M	14.37	14.63	15.33
		s	3.63	4.70	3.92
	b_3	M	8.32	11.72	10.82
		s	4.45	5.56	5.19
	b_1	M	13.53	18.10	17.09
		s	3.18	7.78	7.16
a_2	b_2	M	12.58	14.32	14.58
		s	3.81	3.25	4.01
	b_3	M	10.18	9.34	10.39
		s	4.91	2.04	3.27

APPENDIX F

COMPARISONS OF TREATMENT SUMS

TABLE 19

ELBOW EXTENSION INITIAL SEGMENT IMPULSE:

COMPARISON OF TREATMENT SUMS FOR ABILITY

ΣB_1	ΣB_2	ΣB_3	Σa^2	D_i	MS_{D_i}
928.1	876.0	760.3			
1	0	-1	2	167.8	2011.2*
0	1	-1	2	115.7	956.2*
1	-1	0	2	52.1	139.9*

$$F^1 = (k-1)\ F_{1-\alpha}(k-1,\ df_2)$$

$$= 2\ F_{0.99}\ (2,\ 36)$$

$$= 2 \times 5.25$$

$$= 10.5$$

Smallest significant value:

$$(F^1)(S^2) = 10.5 \times 8.263$$

$$= 86.8$$

*Significant at the 0.01 level.

TABLE 20

SHOULDER EXTENSION WORK OUTPUT:

COMPARISON OF TREATMENT SUMS FOR ABILITY

ΣB_1	ΣB_2	ΣB_3	Σa^2	D_i	MS_{D_i}
4989.7	4721.7	3252.4			
1	0	-1	2	1737.3	215586.5*
0	1	-1	2	1469.3	154203.0*
1	-1	0	2	268.0	5130.3

$$(F^1)(S^2) = 10.5 \times 890.7$$
$$= 9352.4$$

* Significant at the 0.01 level

TABLE 21

ELBOW EXTENSION WORK OUTPUT:

COMPARISON OF TREATMENT SUMS FOR ABILITY

ΣB_1	ΣB_2	ΣB_3	Σa^2	D_i	MS_{D_i}
2563.3	2403.0	1701.6			
1	0	-1	2	861.7	53037.6*
0	1	-1	2	701.4	35140.1*
1	-1	0	2	160.3	1835.4

$$(F^1)(S^2) = 10.5 \times 206.519$$
$$= 2168.4$$

* Significant at the 0.01 level

TABLE 22

SHOULDER EXTENSION STATIC MOMENT:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
4560.9	5395.9	5410.6			
-1	0	1	2	849.7	51570.7*
-1	1	1	2	834.7	49766.0*
0	-1	1	2	15.0	16.1

$$(F^1)(S^2) = 10.5 \times 127.727$$
$$= 1341.2$$

*Significant at the 0.01 level

TABLE 23

ELBOW EXTENSION STATIC MOMENT:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
3430.3	3856.4	3726.8			
-1	1	0	2	426.1	12968.7*
-1	0	1	2	296.5	6279.4*
0	1	-1	2	129.6	1199.7*

$$(F^1)(S^2) = 10.5 \times 66.6$$
$$= 699.4$$

*Significant at the 0.01 level

TABLE 24

SHOULDER EXTENSION INITIAL SEGMENT IMPULSE:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
719.8	814.6	837.4			
-1	0	1	2	117.6	987.8*
-1	1	0	2	94.8	641.9*
0	-1	1	2	22.8	37.1

$$(F^1)(S^2) = 10.5 \times 4.65$$
$$= 48.8$$

* Significant at the 0.01 level

TABLE 25

ELBOW EXTENSION INITIAL SEGMENT IMPULSE:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
792.0	898.4	874.2			
-1	1	0	2	106.4	808.6*
-1	0	1	2	82.2	482.6*
0	1	-1	2	24.2	41.8*

$$(F^1)\ (S^2) = 10.5 \times 3.863$$
$$= 40.6$$

* Significant at the 0.01 level

TABLE 26

SHOULDER EXTENSION EXTENDED SEGMENT IMPULSE:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
2498.4	2799.2	2781.7			
-1	1	0	2	300.8	6462.9*
-1	0	1	2	283.3	5732.8*
0	1	-1	2	17.5	21.9

$$(F^1)(S^2) = 10.5 \times 35.674$$
$$= 374.6$$

* Significant at the 0.01 level

TABLE 27

ELBOW EXTENSION EXTENDED SEGMENT IMPULSE:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
1414.1	1603.2	1560.0			
-1	1	0	2	185.1	2447.3*
-1	0	1	2	141.9	1438.3*
0	1	-1	2	43.2	133.3*

$$(F^1)(S^2) = 10.5 \times 11.534$$
$$= 121.1$$

* Significant at the 0.01 level

TABLE 28

SHOULDER EXTENSION WORK OUTPUT:

COMPARISON OF TREATMENT SUMS FOR DAYS

ΣC_1	ΣC_2	ΣC_3	Σa^2	D_i	MS_{D_i}
3848.3	4518.6	4601.8			
-1	0	1	2	753.5	40554.4*
-1	1	0	2	665.3	31616.0*
0	-1	1	2	88.2	555.7

$$(F^1)(S^2) = 10.5 \times 244.922$$

$$= 2571.7$$

* Significant at the 0.01 level

TABLE 29

SHOULDER EXTENSION STATIC MOMENT:

COMPARISON OF TREATMENT SUMS FOR TRIALS

ΣD_1	ΣD_2	ΣD_3	ΣD_4	Σa^2	D_i	MS_{D_i}
4054.4	3781.9	3803.2	3727.6			
1	0	0	-1	2	326.8	7628.4*
1	-1	0	0	2	272.5	5304.0*
1	0	-1	0	2	251.2	4507.2*
0	0	1	-1	2	75.6	408.2
0	1	0	-1	2	54.3	210.6
0	-1	1	0	2	21.3	32.4

$$(F^1)(S^2) = 15.75 \times 38.816$$

$$= 611.4$$

* Significant at the 0.01 level

TABLE 30

ELBOW EXTENSION WORK OUTPUT:

COMPARISON OF TREATMENT SUMS FOR TRIALS

ΣD_1	ΣD_2	ΣD_3	ΣD_4	Σa^2	D_i	MS_{D_i}
1540.0	1661.5	1709.0	1757.3			
-1	0	0	1	2	217.3	3372.8*
-1	0	1	0	2	169.0	2040.1*
-1	1	0	0	2	121.5	1054.4*
0	-1	0	1	2	95.8	655.5*
0	0	-1	1	2	48.3	166.6
0	-1	1	0	2	47.5	161.2

$$(F^1)(S^2) = 15.75 \times 22.269$$

$$= 350.7$$

* Significant at the 0.01 level

APPENDIX G

SWIM PERFORMANCE ANALYSIS

TABLE 31

THREE WAY ANALYSIS OF VARIANCE

SWIM PERFORMANCE FOR 25 METRES

Source of variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	43.562	3.04
B (Ability)	2	585.219	40.88*
AB	2	5.062	0.35
Subjects w. groups	36	14.316	
Within Subjects			
C (Days)	1	18.937	3.39
AC	1	39.187	7.02*
BC	2	11.874	2.13
ABC	2	9.000	1.61
C x subj. w. groups	36	5.584	

* Significant of the 0.05 level

AC SUMMARY TABLE (SECONDS)

	C_1	C_2	C_3	
A_1	516.4	492.4	472.3	1481.1
A_2	518.7	507.2	529.3	1555.2
	1035.1	999.6	1001.6	

TABLE 32

THREE WAY ANALYSIS OF VARIANCE

SWIM PERFORMANCE FOR 50 METRES

Source of variation	Conservative df	Mean Squares	F
<u>Between Subjects</u>			
A (Treatments)	1	355.12	5.68*
B (Ability)	2	3762.53	60.21*
AB	2	34.19	0.55
Subjects w. groups	36	62.49	
<u>Within Subjects</u>			
C (Days)	1	74.75	2.56
AC	1	254.00	8.71*
BC	2	89.12	3.05
ABC	2	26.88	0.92
C x subj. w. groups	36	29.18	

* Significant at the 0.05 level

AC SUMMARY TABLE (SECONDS)

	C_1	C_2	C_3	
A_1	1209.5	1148.8	1101.1	3459.4
A_2	1212.8	1208.8	1249.3	3670.9
	2422.3	2357.6	2350.4	

TABLE 33

THREE WAY ANALYSIS OF VARIANCE

SWIM PERFORMANCE FOR 100 METRES

Source of variation	Conservative df	Mean Squares	F
Between Subjects			
A (Treatments)	1	3225.0	8.97*
B (Ability)	2	23055.0	64.14*
AB	2	667.5	1.86
Subjects w. groups	36	359.4	
Within Subjects			
C (Days)	1	1615.0	10.19*
AC	1	1507.0	9.50*
BC	2	286.0	1.80
ABC	2	62.5	0.39
C x subj. w. groups	36	158.5	

* Significant at the 0.05 level

AC SUMMARY TABLE (SECONDS)

	C_1	C_2	C_3	
A_1	2900.2	2680.3	2545.8	8126.3
A_2	2936.5	2889.5	2937.7	8763.7
	5836.7	5569.8	5483.5	

APPENDIX H

ESTIMATES OF VARIANCE COMPONENTS

TABLE 34

SHOULDER EXTENSION STATIC MOMENT:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	1144.46	12.52	14.8
B (Trials)	3	53.16	0.60	0.7
C (Subjects)	20	530.78	34.71	41.2
BC	60	18.16	2.85	3.4
AC	40	105.67	24.02	28.5
AB	6	6.88	0.00	0.0
Residual	120	9.62	9.62	11.4

TABLE 35

ELBOW EXTENSION STATIC MOMENT:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	181.04	20.94	38.3
B (Trials)	3	6.31	0.02	0.0
C (Subjects)	20	255.16	17.68	32.4
BC	60	11.17	1.56	2.9
AC	40	38.26	7.94	14.5
AB	6	0.45	0.00	0.0
Residual	120	6.49	6.49	11.9

TABLE 36

SHOULDER EXTENSION INITIAL SEGMENT IMPULSE:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	16.502	0.163	7.9
B (Trials)	3	0.359	0.000	0.0
C (Subjects)	20	10.772	0.615	29.9
BC	60	1.068	0.186	9.0
AC	40	2.838	0.582	28.4
AB	6	0.457	0.000	0.0
Residual	120	0.510	0.510	24.8

TABLE 37

ELBOW EXTENSION INITIAL SEGMENT IMPULSE:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	9.375	0.081	4.7
B (Trials)	3	0.681	0.005	0.3
C (Subjects)	20	11.649	0.758	44.0
BC	60	0.345	0.011	0.6
AC	40	2.525	0.553	32.1
AB	6	0.345	0.002	0.1
Residual	120	0.312	0.312	18.1

TABLE 38

SHOULDER EXTENSION EXTENDED SEGMENT IMPULSE:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	176.301	1.837	10.7
B (Trials)	3	0.648	0.000	0.0
C (Subjects)	20	114.090	7.520	43.9
BC	60	4.289	0.710	4.1
AC	40	21.724	4.891	28.5
AB	6	2.444	0.014	0.1
Residual	120	2.160	2.160	12.6

TABLE 39

ELBOW EXTENSION EXTENDED SEGMENT IMPULSE:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	31.768	0.304	6.3
B (Trials)	3	1.495	0.015	0.3
C (Subjects)	20	33.169	2.184	45.2
BC	60	1.003	0.085	1.8
AC	40	6.712	1.491	30.9
AB	6	0.278	0.000	0.0
Residual	120	0.748	0.748	15.5

TABLE 40

SHOULDER EXTENSION WORK OUTPUT:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	1141.96	11.83	8.6
B (Trials)	3	16.36	0.00	0.0
C (Subjects)	20	999.76	69.49	50.6
BC	60	35.27	5.90	4.3
AC	40	148.18	32.65	23.8
AB	6	17.87	0.02	0.0
Residual	120	17.58	17.58	12.8

TABLE 41

ELBOW EXTENSION WORK OUTPUT:

ESTIMATES OF VARIANCE COMPONENTS

Source	df	Mean Squares	Estimated σ^2	% of total
A (Days)	2	98.25	0.72	1.9
B (Trials)	3	25.17	0.31	0.8
C (Subjects)	20	293.05	20.63	54.0
BC	60	9.74	1.06	2.8
AC	40	42.24	8.92	23.4
AB	6	2.41	0.00	0.0
Residual	120	6.55	6.55	17.2

APPENDIX I

MEANS ACROSS TRIALS

TABLE 42

MEANS FOR TRIALS

Measure		d_1	d_2	d_3	d_4	Units
Shoulder Extension Static Moment						
	a_1	33.47	30.80	30.90	30.42	N.m
	a_2	30.89	29.23	29.46	28.75	
Elbow Extension Static Moment						
	a_1	21.92	21.58	21.62	20.98	N.m
	a_2	22.59	22.16	21.82	22.14	
Shoulder Extension Initial Segment Impulse						
	a_1	5.016	4.857	4.828	5.050	$Kg.m^2/s$
	a_2	4.365	4.517	4.517	4.514	
Elbow Extension Initial Segment Impulse						
	a_1	4.865	5.082	5.021	5.194	$Kg.m^2/s$
	a_2	5.005	5.101	5.210	5.230	
Shoulder Extension Extended Segment Impulse						
	a_1	16.83	16.51	16.57	17.11	$Kg.m^2/s$
	a_2	15.19	15.44	15.29	15.30	
Elbow Extension Extended Segment Impulse						
	a_1	8.76	9.11	9.09	9.31	$Kg.m^2/s$
	a_2	8.98	8.99	9.22	9.27	
Shoulder Extension Work Output						
	a_1	27.63	27.15	27.29	28.95	J
	a_2	23.01	24.23	23.66	23.86	
Elbow Extension Work Output						
	a_1	11.83	13.34	13.31	13.96	J
	a_2	12.61	13.03	13.82	13.93	